NASA CR-135119 SUPPLEMENT A
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PERFORMANCE, EMISSIONS, AND PHYSICAL CHARACTERISTICS OF A ROTATING COMBUSTION AIRCRAFT ENGINE

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by

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15. Supplementary Notes

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16. Abstract Since the results reported in this supplement pertain only to the testing accomplished on the modified engine, the original report number NASA CR-135119 should be referred to for the baseline characterization of the RC2-75 engine.

The RC2-75, a liquid-cooled two chamber Rotary Combustion engine (Wankel type), designed for aircraft use, was tested and representative baseline (212 kW, 285 BHP) performance and emissions characteristics established under Contract NAS 3-20030. The results of that testing was reported in report number NASA CR-135119, upon which this supplementary report is dependent for the baseline data. The results of the above testing indicated that with the exception of the HC emission level the baseline engine met or were lower than the then proposed 1980 exhaust emission requirement, but the specific fuel consumption was higher than existing aircraft engines.

For testing accomplished under the current contract, several modifications were incorporated which were designed to reduce the HC emissions and reduce the specific fuel consumption. The modifications included "close-in" surface gap spark plugs, increased compression ratio rotors, and provisions for utilizing either side or peripheral intake ports, or a combination of the two if required.

The exhaust emissions results compared to the then 1980 EPA requirements in pounds per horsepower cycle were met as tabulated below:

	Demonstrated	EPA Standard
HC	0.00186	0.0019
CO	0.03464	0.0420
NO_x	0.00108	0.0015

75% Standard Day rated horsepower brake specific fuel consumption is 283 g/kW-hr (.465 lb/BHP-hr) for the configuration tested at 5500 rpm, 101 BMEP, and 272.5 g/kW-hr (.448 lb/BHP-hr) at 5000 rpm, 111 BMEP.

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SUMMARY

The primary objectives of the follow-on program were to improve the fuel economy and reduce the idle/taxi exhaust emissions by engine modifications including higher compression ratio, relocating the spark discharge closer to the trochoid surface, and adding side intake ports for use during the idle/taxi mode, if required.

Testing was conducted using the basic RC2-75 engine used previously and modified as described herein. Testing under the final revision of the test program resulted in meeting all of the original program objectives.

The testing included a run-in followed by running fuel-air mixture control curves and varied ignition timing sufficient to permit running wide open throttle best power points at 3500, 4000, 4500, 5500, and 6000 rpm, mixture control curves at 45%, 75% and 85% power, and taxi conditions and rich and lean points at 45% and 65% power. Exhaust emissions data were obtained at appropriate conditions sufficient to permit determination of the exhaust emissions in lb/cycle/rated hp.

Three methods of calculating air/fuel ratio from emissions measurements were employed; two carbon balance procedures (one being the Spindt method) and one oxygen balance procedure. Data points were not considered satisfactory unless all three methods agreed within 5% of the measured air/fuel ratio. This was true for all emissions data except idle, as detailed under Section D3.

Calibration of all data gathering instruments and equipment was carried out before and during the engine test program to insure accuracy of the results.

Curves of the performance and emissions data obtained are presented herein, and compared to results obtained prior to the modifications.

The exhaust emissions results compared to the then 1980 EPA requirements in pounds/rated bhp-cycle were:

	Demonstrated	EPA Standard
HC	.00186	.0019
CO	.03464	.0420
NO_x	.00108	.0015

As noted, the proposed (but subsequently withdrawn) EPA emissions requirements were met with the modifications described. It should be noted that the requirements were met using the normal peripheral porting.

The specific fuel economy demonstrated for the modified RC2-75 was 283 g/kW-hr (.465 lb/bhp-hr) at 75% power and 101 BMEP (5450 rpm) and 272.5 g/kW-hr (.448 lb/bhp-hr) at 75% power and 111 BMEP (5000 rpm). The latter would result from rating the engine for take-off at 285 hp and 5500 rpm, instead of 6000 rpm.

INTRODUCTION

For background history of Curtiss-Wright's research and development of the rotary combustion engine, refer to report NASA CR-135119. That report also contains comprehensive data on the characterization of the RC2-75 Rotary Combustion Engine as an aircraft engine, including performance and emissions data of the unmodified engine.

The purpose of the present effort was to determine the improvement in brake specific fuel consumption and exhaust hydrocarbon emissions as a result of several modifications to the basic power section. A description of the unmodified RC2-75 engine is contained in the above noted report. The modifications incorporated for the effort reported herein included:

> Spark discharge relocated closer to the trochoid surface; from .63 inch to .040 inch.
>
> Compression ratio increased from 7.5:1 to 8.5:1.
>
> Provision of side intake ports in addition to the normal peripheral intake ports which could be used independently or in combination to evaluate the effect on performance and exhaust emissions. For the testing conducted herein only the normal peripheral intake port configuration was required.

A copy of the initial test plan is presented as Appendix A, while the modified test plans are presented as Appendices B and C. Technical difficulties experienced as a result of mounting the engine in the test facility and engine rebuilding problems caused some delay and subsequent reduction in test plan scope in accordance with Appendix B. Based upon the encouraging results obtained at that stage of the program, the test plan was again modified to accomplish the testing outlined in Appendix C.

I. PERFORMANCE AND EMISSIONS ENGINE TESTING

A. Test Engine Description (RC2-75)

For a complete description of the unmodified RC2-75 engine as tested for the initial characterization, refer to the report NASA CR-135119. The modifications incorporated under this contract NAS-3-20808 and their anticipated results were as follows:

1. The rotor housings were reworked to permit installation of surface gap type spark plugs, which enabled the spark discharge to be moved closer to the trochoid surface (.040 vs .63 inch). Conventional spark plugs are normally retracted to prevent overheating at high output, but the cooler construction characteristics of the surface gap plugs permits their being closer to the surface. This issue is discussed more fully in the above noted report. This change should significantly improve combustion regularity at idle and taxi conditions and thus reduce HC emissions level. It should also reduce the specific fuel consumption over most of the operating range. Figure 1 shows the two spark plug configurations.

2. The 7.5:1 compression ratio rotors were replaced with 8.5:1 compression ratio rotors which had symmetrical combustion chamber pockets, and would assist in reducing specific fuel consumption. The improvement in fuel economy of these two modifications as tested in an RC1-75 rig engine is shown in Figure 37 of the above noted report.

3. A new intermediate housing incorporating side intake ports was fabricated and the end housings were reworked to provide "dummy" side intake ports for proper interseal cavity pressure balancing. An intake manifold modification was also designed and procured which would permit the engine to be configured for operating with either peripheral or side intake porting, or a combination of both. This manifold configuration is shown in Figure 2. The objective was to use only the side intake ports during idle and taxi, since the reduced port overlap would cut down charge dilution, improve combustion, and reduce HC. At higher speed and power the peripheral ports were to have been used either alone or in combination with the side ports. As noted previously, the overall cycle emissions requirements were met without having to resort to either the separate side intake ports or a combination of side and peripheral ports at the idle and taxi conditions.

4. Provisions were made for using a transistorized multi-strike high energy ignition system which was claimed to be able to fire the close-in surface gap spark plugs consistently in case the standard magneto failed to do so at low power and speeds.

5. Later in the test program, after the transistorized ignition system failed to show an improvement in firing regularity over the standard magneto, a method of attaching the magneto to the engine so that the ignition timing could be remotely controlled with a push-pull cable was designed and fabricated to facilitate selecting the optimum timing at the various speed and power conditions. Still later it was found that a basic incompatability between the Hall-Effect triggering and the electronic ignition unit had negated the evaluation of the transistorized ignition system, but depletion of funds prevented a final evaluation of the system. The problem has since been corrected, but the system was not fully evaluated before the program ended.

B. Test Equipment Description

1. Test Cell Equipment and Configuration

The RC2-75 engine for the follow-on contract testing was moved from the Test Cell WX-24 to WX20-5 because the former facility had in the interim been converted to test an engine configuration for another contractual program.

Test Cell No. WX20-5 is a complete induction dynamometer test facility with absorbing capacity of 400 hp, complete services, instrumentation and control.

Selection of this facility necessitated absorbing the power from the flywheel end of the engine rather than the propeller shaft. This method of power absorbtion does not account for the power transmission losses in the reduction gearing. The estimated gain using this method of power absorbtion is less than 1%, and both Curtiss-Wright and NASA agreed to accept the data obtained as valid. Figure 2 of Appendix A shows a schematic of the engine and dynamometer drive line system. Connection to the dynamometer was accomplished by an appropriate coupling at the flywheel end of the engine. Starting was provided by the Eaton 25 hp capacity starting motor through a Formsprag clutch. Power absorbtion was achieved by the Eaton induction type dynamometer.

Figure 3 presents an overall photographic view of the engine and drive line consistent with the schematic presented in the previous figure.

Figure 4, taken from the propeller shaft end of the engine, shows the carburetor and intake manifold end and one of the two bellows type exhaust pipes connected to the test stand exhaust manifold. Also shown is the push-pull cable arrangement for remotely rotating the magneto for variable ignition timing and the coolant in and out lines connecting to the test stand coolant system.

Figure 5 presents a photograph of the Tester's control station within the control room. As shown, the tester has clear visibility into the engine and dynamometer room while having within reach all primary test controls, instrumentation, and gauges. Included are engine controls at the desk top (ignition switches, throttle, fuel/air mixture and ignition advance), dynamometer and starter motor controls at the left, airflow (calibrated bellmouth and inclinometer), fuel flow (Flowtron mass flowmeter), load (cell), rpm (digital counter), with overspeed protection and dynamometer warnings conveniently located immediately surrounding the tester's primary work zone.

Figure 6 presents additional auxilliary gauges, automatic controls for coolant and oil temperature and oil pressure, and instrumentation to monitor vibration, ignition timing, and various temperatures and pressures, all within easy reach of the tester from his primary work zone.

Test Cell WX20-5 includes provisions for measuring the engine coolant flow and controlling its temperature. There is an oil supply system with cooling and weight (for flow and consumption) provisions. Flow pressures and temperatures are controlled and monitored in the coolant and lube systems.

2. Test Cell Instrumentation

a. Description

Basic instrumentation consisting of selected usage and calibration of a portion of that instrumentation normally available at WX20-5.

In addition to the airflow, fuel flow, and power measurement systems previously discussed, various other pressure gauges, mercury and water manometers, flowmeters, thermocouples, I/C and C/A temperature indicators etc were utilized to record for each test point the basic variables outlined in the original Test Plan (Appendix A). Pages 7 and 8 of the Test Plan show the range and accuracy of the instrumentation used.

Figures 7 and 8 present photographs showing the basic arrangement and equipment used.

b. Calibration

Instrumentation (and Test Equipment) was calibrated and maintained to Curtiss-Wright Quality Control Order No. 03-2 Revision F dated 3/12/79 (Instruments), Quality Control Order No. 03-6 Revision F dated 3/21/78 (Standards). The frequency of calibration was adjusted to suit the test schedule, with pre-test and re-calibration during test as

required to suit the interrupted testing. Exhaust emission Scott Model 108-H Exhaust Gas Analysis System was calibrated by Curtiss-Wright Engineering personnel with occasional assistance from Scott Environmental Systems and Beckman Instruments, Inc.

3. Emissions Measuring Equipment

a. Equipment Description

The same equipment as originally described in detail in the report NASA CR-135119 was used for this test, the only change being the elimination of the sample-in gas modifications described in the above noted report. These modifications were eliminated with the concurrence of NASA since the testing accomplished previously established the residence time for the instrumentation used and were as agreed between Curtiss-Wright and NASA.

b. Calibration

Before the emissions test portion of the current program a full calibration of all analyzers was performed as described in the report NASA CR-135119.

c. Operation

Again, the operation of the emissions equipment was as described in the above report.

C. Test Procedures

The test procedure was generally in accordance with the test plans as submitted by Curtiss-Wright and approved by NASA. The original test plan is listed in Appendix A and the reduced scope test plan is listed in Appendices B and C. The basic procedures consisted of the following discrete phases:

1. Engine Break-In

A break-in period consisted of approximately thirty minutes per point over a wide load and speed range as listed in the above noted appendices. Static air leak checks indicated good sealing after the run-in and at completion of the testing.

2. Basic Calibration

Complete calibration of the exhaust emissions measuring equipment, the test cell instrumentation, basic test equipment devices, and operation of the engine to support these individual and combined calibration procedures or to define selected engine parameters was performed as described in the report NASA CR-135119.

3. Emission Measurement

This phase specifically relates to the EPA cycle emissions determination. There was a wide overlap with item 2 similar to that expierenced with the unmodified engine to obtain emissions data at a variety of engine operational conditions.

Also, as before, during the testing of the unmodified engine, extensive efforts were required to maintain and service the Exhaust Gas Analysis System to obtain quality data.

The same desk top computer program as described in report NASA CR-135119 was utilized to verify the reliability of the test point data prior to proceding to the next data point.

4. Performance

Testing was as noted in the above report with respect to stabilization of parameters, recording of test data, etc.

5. EPA Cycle

An emissions test was conducted in basic conformance with EPA procedures defined in the Federal Register, except the specific sequence was not followed. Since the prescribed tests call for stabilization at each point, which was adhered to, the sequence used should not affect the results. The test was conducted to determine the emissions signature of the modified RC2-75 engine compared to the former EPA 1980 emissions requirements, and to compare the emissions to the original configur tion of Report NASA CR-135119.

All operating mode data were obtained at 33° BTC ignition timing with .073 fuel/air ratio maintained at all conditions except taxi, where a higher spark angle was maintained, and idle, where idle mixture was set for best idle of the selected power and speed condition.

A sample of the fuel being used (Aviation Gasoline, Grade 100/130 with 1% AD 65 Grade 30 oil added) was tested and found to meet the specifications in ASTM D910-75. The results are in Appendix D.

D. Test Results and Discussion

Complete log sheets, emissions strip charts, calibrations, and data reduction for the test are on file and available for inspection.

1. Full Throttle Performance

Observed full throttle performance of this configuration RC2-75 engine, 8.5:1 compression ratio and close-in spark plugs, is

shown on Figure 7. Nominally the data were obtained at .073 f/A ± approximately 3%. Anticipated improvements due to increased compression ratio are reductions in exhaust gas temperature and specific fuel consumption. Exhaust gas temperature reduction with increase in compression from 7.5 to 8.5 was 75 to 100°F. Figure 8 shows the standard day performance, using the correction methods of Report NASA CR-135119, and adjusting the BSFC to a constant fuel air ratio of .073. In the range of fuel air ratios tested (the best power range) a negligible effect would be seen in power and BSFC would be directly proportional to the fuel air ratio. Corrected power at take-off rpm, 6000, was 221 kW or 296 BHP compared to the engine rating of 285 BHP.

Figure 9 is a comparison of the 7.5:1 (Ref. Report NASA CR-135119) and the 8.5:1 compression ratio configurations power and fuel consumption under standard day conditions and equal mixture strengths. The difference in power at constant speed can only be explained by differences between engines, since Curtiss-Wright's experience with varying compression on its various Rotary Engines has shown basically no variation in full throttle power but the normal approximately 3 percent variation in fuel consumption for each compression ratio change. By inspection, BSFC is noted to have improved approximately 7 percent over the speed range with the probability that the greater than theoretical reduction is attributable to the close-in spark plugs and better charge mixing in the combustion chamber as associated with higher mass transfer velocities in the combustion pocket of the rotors. This is in very close agreement with the RC1-75 testing shown on Figure 37 of Report NASA CR-135119 and as discussed in that report.

2. Part Throttle Fuel Consumption

Part throttle fuel consumption was evaluated at several percentages of take-off power, 285 BHP, on the take-off propeller load curve. Ignition timings for the cruise range mixture strengths were determined by obtaining variable spark angle curves at 45, 55 and 75% power on the 285 hp/6000 rpm propeller load curve and at 75% power on a 285 hp/5500 rpm propeller load curve. Figures 10, 11, 12 and 13, at the above operating conditions, illustrate the effect of ignition on BSFC, et al at constant mixture strength, .065 - .066.

Based upon the above determined ignition timings, constant power mixture control curves were run at 45, 75 and 85% power on the 285 hp/6000 rpm propeller load curve with best power and best economy data obtained at 55 and 65% power. A mixture control curve also defined best fuel consumption at 75% power and 5000 rpm which falls on the 285 hp/5500 rpm propeller load curve. The above curves are shown in Figures 14 through 17. Figure 18 summarizes the fuel consumption and airflow requirements for best power and best economy operation. On the

285 hp/6000 rpm T.O. propeller load curve a minimum fuel consumption of 283 g/kW-hr, .465 lb/BHP-hr, is obtained at 75% power. Based on a 285 hp/5500 rpm propeller load curve, 75% power would produce a BSFC of 272.5 g/kW-hr, .448 lb/BHP-hr, as determined from Figure 16. This is a result of rpm reduction and increase in BMEP from 101 psi at 5500 to 111 at 5000 rpm with a 3.5% fuel consumption improvement effected.

Figure 19 provides a comparison of fuel consumption improvements and operational characteristics of the RC2-75 engine when modified from 7.5:1 compression ratio rotors and .63 inch retracted spark plugs, Engine No. 7521-8 reported in Report NASA CR-135119, to 8.5:1 compression ratio and close to the trochoid (.040 inch) spark plug electrodes. The modification as shown provides the capability to operate at leaner mixtures and more advanced ignition timings which resulted in at 75% cruise a reduction in specific fuel consumption of 13.5 percent, where only 3% can be attributed to the compression ratio increase. Positioning the spark plug electrodes close to the trochoid surface improves scavenging of the spark plug cavity thus reducing burned gas dilution. This reduction permits the engine to obtain more consistent combustion at leaner mixtures resulting in the major portion of the SFC reduction. A secondary benefit is the reduction of exhaust gas temperatures.

3. EPA Exhaust Emission Test Results

Figure 20 is a tabulation of data related to the emission cycle test with the engine parameters of power, airflow, and fuel flow, raw emissions concentration, correction factor and calculated exhaust density, emission rates, cycle emissions and cycle emissions per rated horsepower. Cycle emission rates are compared with the former 1980 EPA emissions requirement.

Emission cycle testing was conducted during the initial build of this configuration and indicated the lb/cycle/rated hp HC emissions to be 14% higher than the standard, which constituted an 18% improvement over the 7.5:1 compression ratio engine. Since the taxi mode HC emissions accounted for 44% of the total, parametric curves were obtained at 28 hp/2660 rpm with the variables of ignition timing and fuel air ratio. Emission results, in lbs/hr, and specific fuel consumption effects are shown on Figures 21 and 22. The results of this survey are incorporated in the tabular data of Figure 20 and reduce the HC emissions to 2.1% below the former standard for an overall improvement of 29.5%.

With the increase in compression ratio a minor reduction, .0374 to .0346 lb/cycle/rated hp, in CO emissions amounting to 10% was effected. As could be projected, NO_x emissions increased significantly as the compression ratio was raised. The increase was approximately 27% resulting in the emissions being only 28% below the former EPA standard.

During the idle emissions testing only, the calculated fuel-air ratio using two carbon balance calculations and one oxygen balance calculation, did not agree with the measured fuel-air ratio within 5%. The apparent discrepancy is believed to result from excess EGR. Thus the actual engine airflow at this extreme throttled operating point, in view of the high port overlap, is higher than measured. Correcting these data for estimated airflow to give oxygen and carbon balance changes the results less than the 1-1/2% HC margin, and still meets the emissions specification. The emissions data shown in Figure 20 shows as-measured data, and not adjusted as discussed above.

II. CONCLUSIONS

A. The RC2-75 Rotary Aircraft engine, modified for close-in surface gap type spark plugs and using 8.5:1 compression ratio rotors does successfully meet the former 1980 EPA exhaust emissions requirements without any after treatment. The engine emissions, compared to the 1980 EPA proposed requirements, were 1.5% below for HC emissions, 17.5% below for the CO emissions, and 27.9% below for the NO_x emissions.

B. The former 1980 EPA exhaust emissions requirements were met or bettered using the normal peripheral intake porting preferred for high power operation, although provisions had been incorporated for side and/or combination intake porting should that configuration have been required to meet the HC emissions requirement in the taxi and idle operational regimes.

C. Compared to the exhaust emissions previously obtained with the unmodified RC2-75 engine described in report NASA CR-135119, the emissions of the modified engine were 29.5% below for HC, 10% below for CO, and 28% above for NO_x. The increase in NO_x emissions still results in bettering the requirements, as noted in II.A., above.

D. The 75% rated power (159.3 kW/5450 rpm) brake specific fuel consumption was improved from 328.5 g/kW-hr (.540 lb/bhp-hr) to 283 g/kW-hr (.465 lb/bhp-hr) with the modified engine compared to the unmodified version.

E. An additional 3.5% fuel consumption improvement can be effected at 75% power by rating the engine at 285 BHP at 5500 rpm instead of 6000 rpm. Under these conditions the minimum fuel consumption at 159.3 kW, 5000 rpm is 272.5 kW-hr (.448 lb/bhp-hr).

F. Further reduction in fuel consumption was limited during the current testing by a lean instability problem (misfiring), that occurred while running the mixture control curves. It is expected that further improvements in BSFC, as a result of operating at leaner mixtures, would be obtained with further development aimed at reducing the lean instability. The exact causes are not known, but a primary reason is thought to be the inability of the particular ignition system/spark plug configuration used to consistently light off the very lean mixtures.

III. RECOMMENDATIONS

Having established that the baseline RC2-75 engine exhaust emissions and fuel consumption can be improved with relatively minor configuration changes such as close-in spark plugs and increased compression ratio, several additional changes should be investigated to determine if performance can be further improved. These additional improvements should include:

A. Fuel Injection

The improved bank-to-bank charge distribution over the standard carburetor and intake manifold should improve performance throughout the entire operating regime.

B. Plasma spray the rotor combustion face with a refractory material.

This may help improve combustion regularity and reduce wall quenching by increasing the rotor surface temperature.

C. Spark-plug/Ignition System Development

The improvements gained with close-in surface gap type spark plugs and the magneto ignition system suggest further improvements in combustion regularity at lean mixtures could probably be effected by further development of spark-plug/ignition system compatibility. This should include evaluation of the Autotronics ignition system which is now available but was not adequately evaluated during this test. Elimination of the lean instability is the primary goal here.

D. Further increased compression ratio rotors.

IV. FIGURES

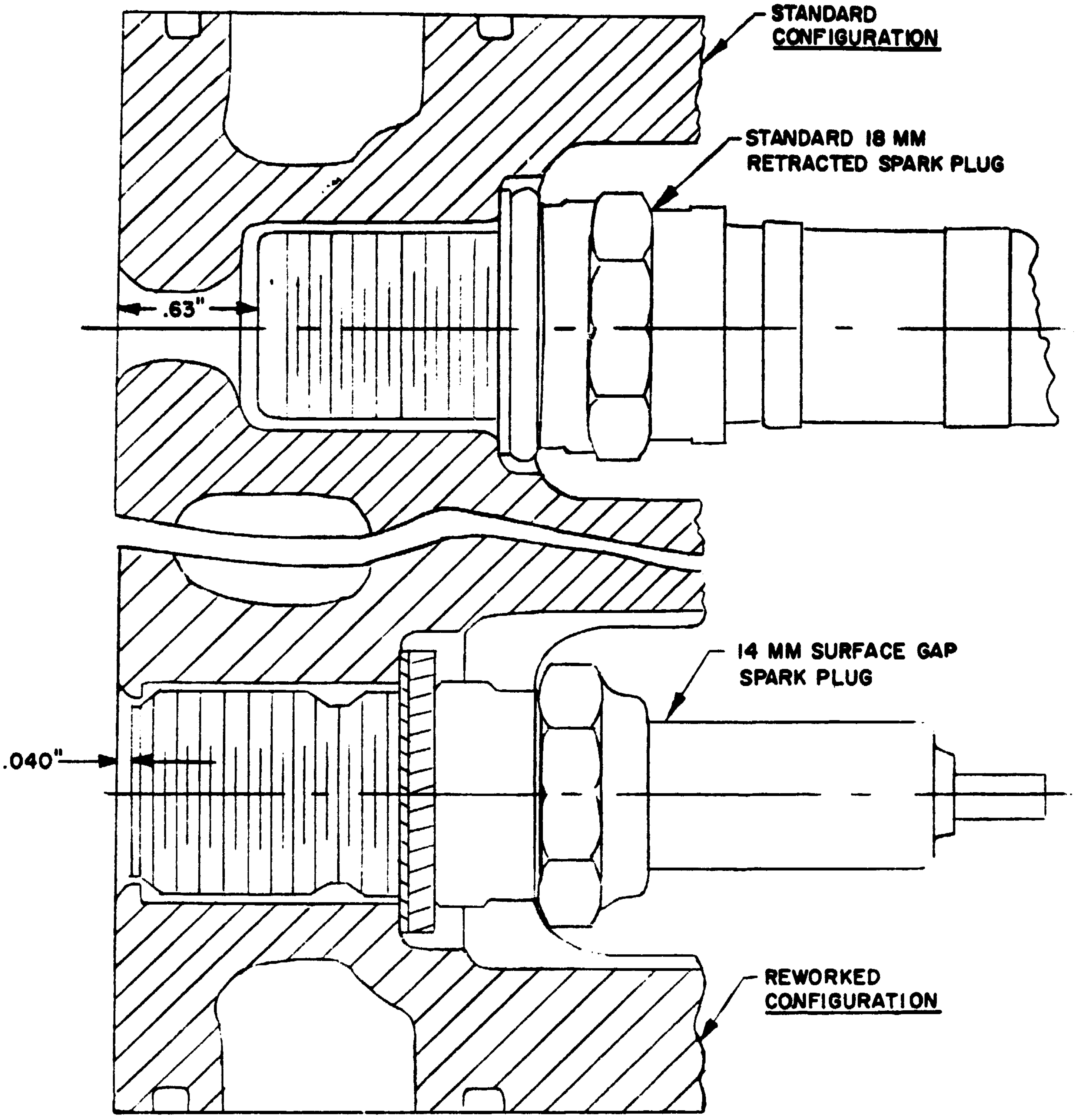
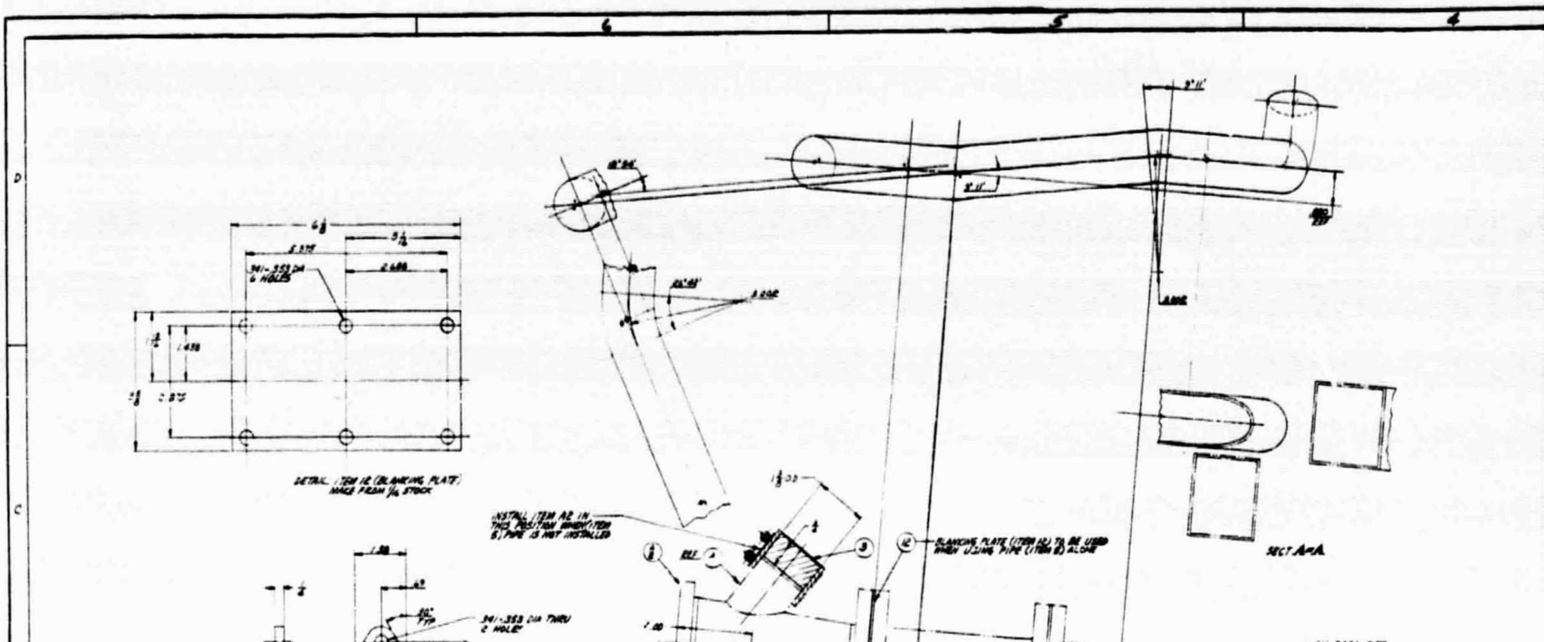


Figure 1. Comparison of Configurations - Close-In Surface Gap Spark Plug and Standard Retracted Spark Plugs Tested in the RC2-75 Engine.



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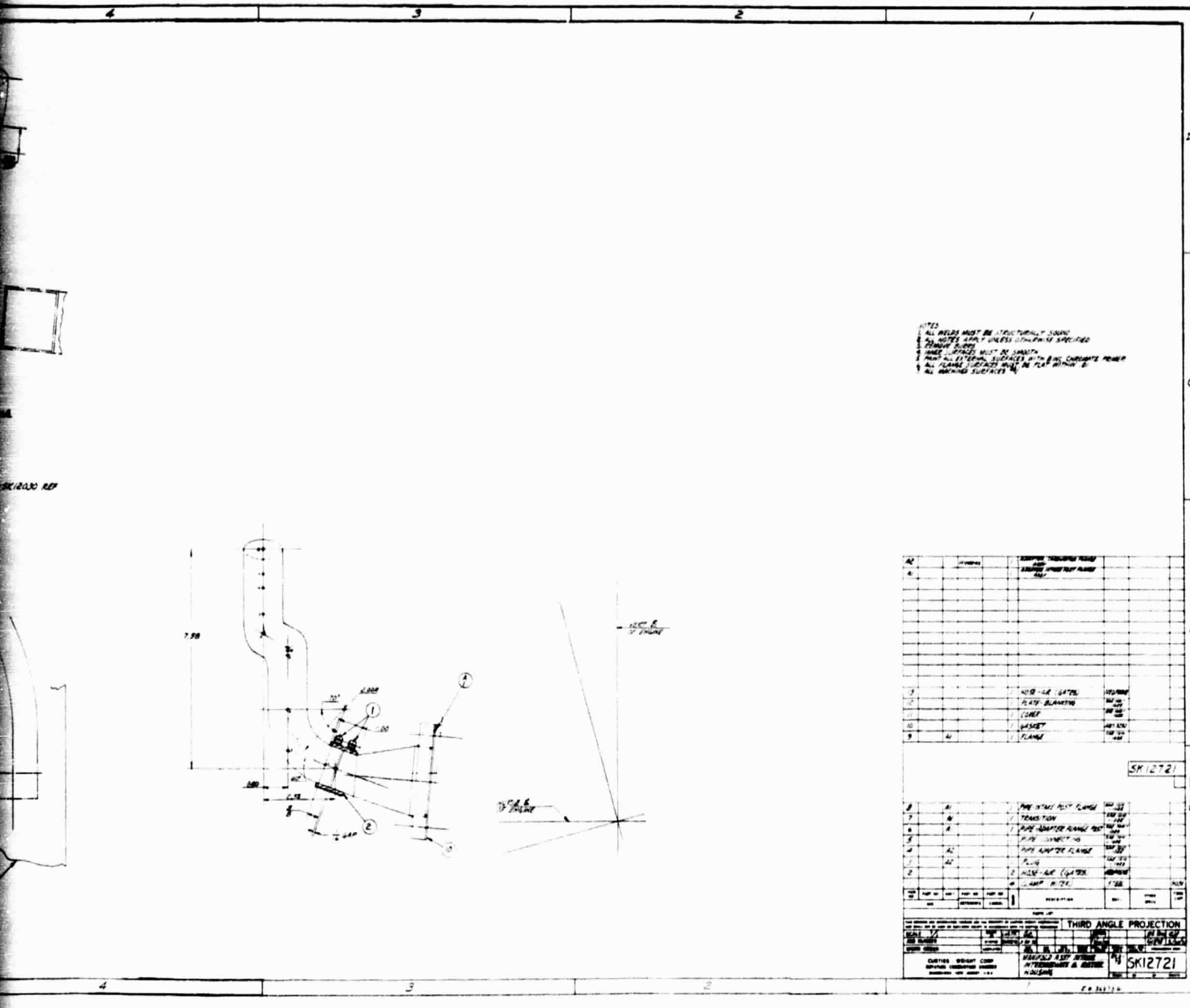

Figure 2. Manifold and Piping Configuration for Utilizing S
Intake Ports on the RC2-75 Engine - SK12721.

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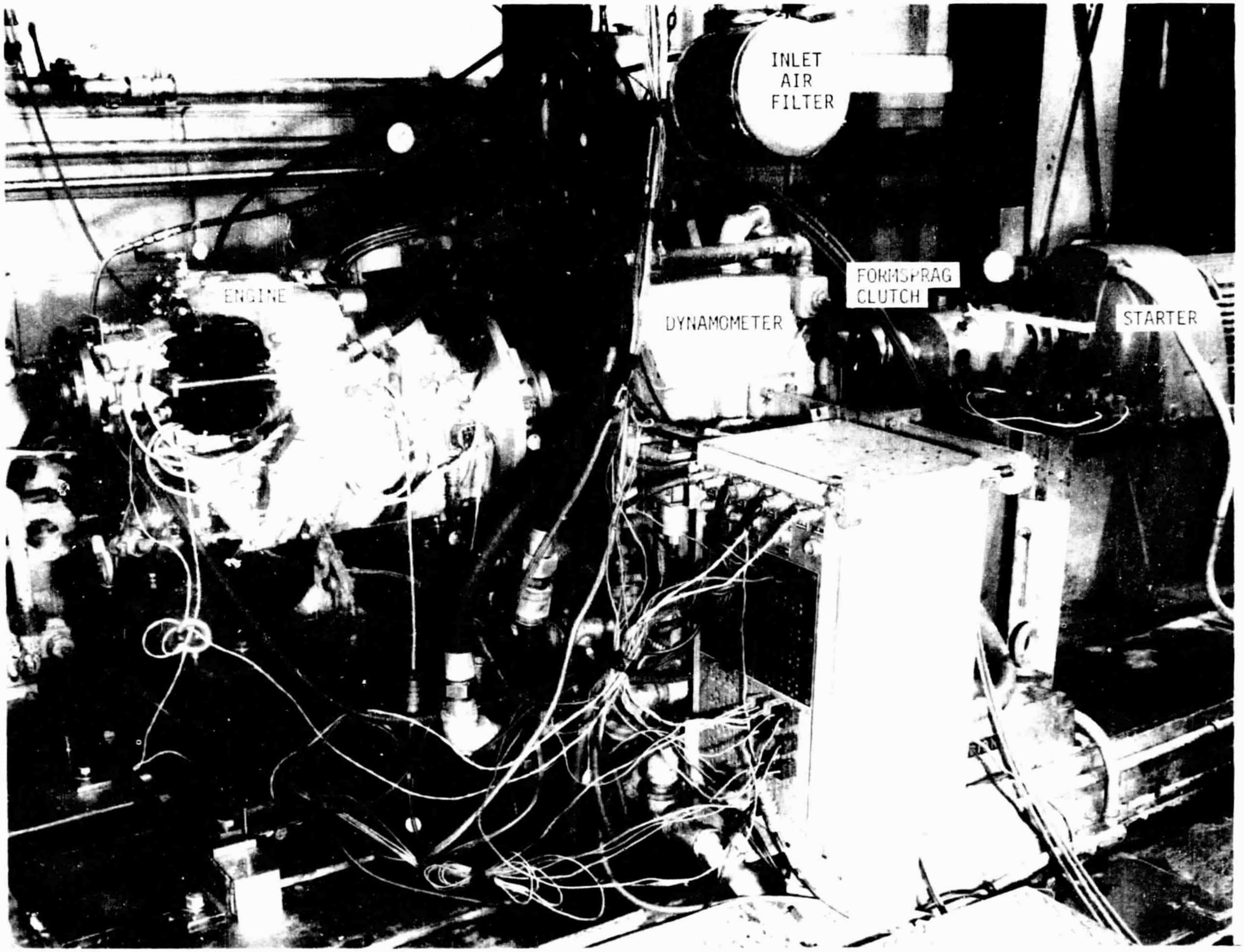

Figure 3. The RC2-75 Engine and Dynamometer Drive Line in the Test Cell.

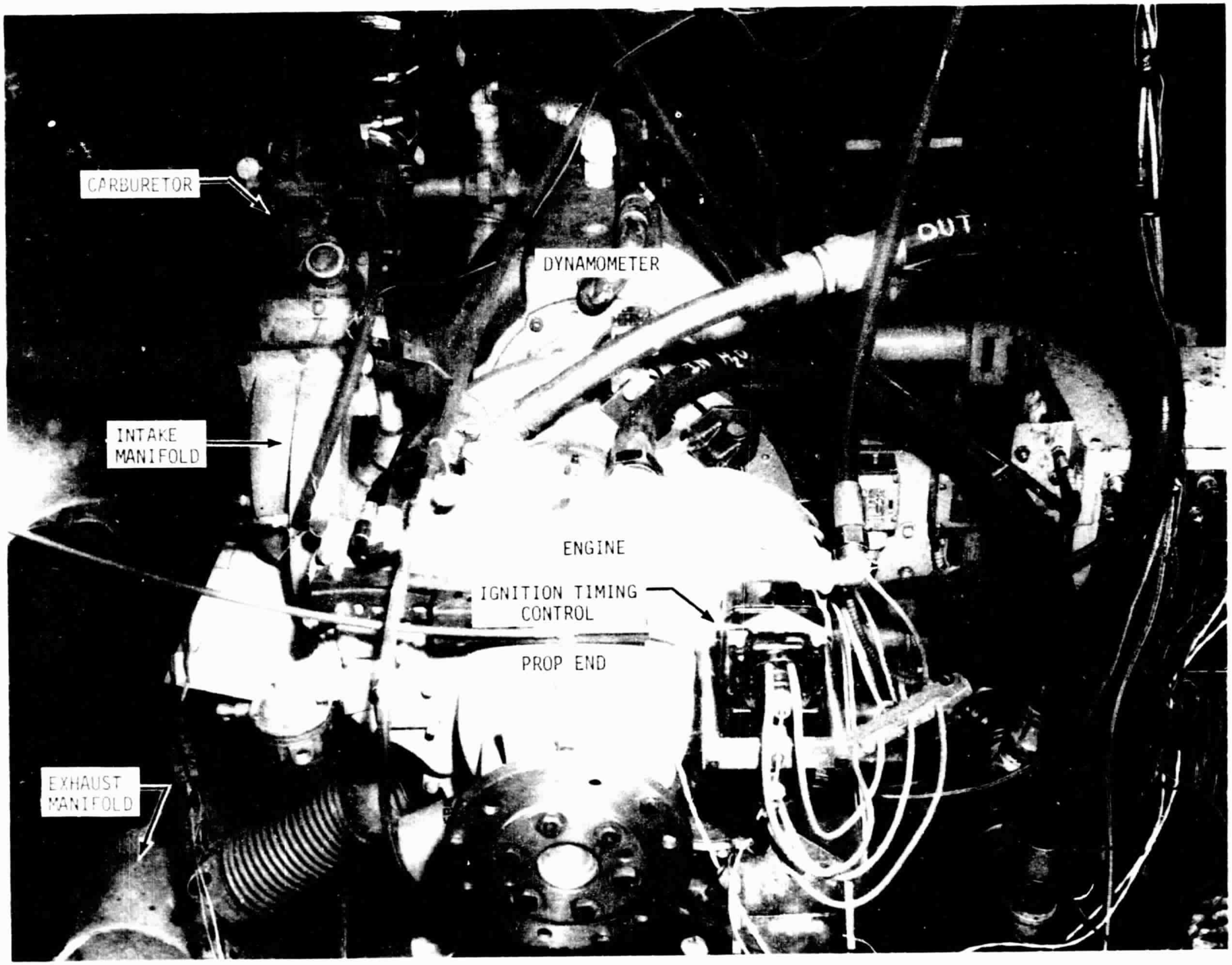

Figure 4. Close-Up from Propeller End of the RC2-75 Engine in the Test Cell.

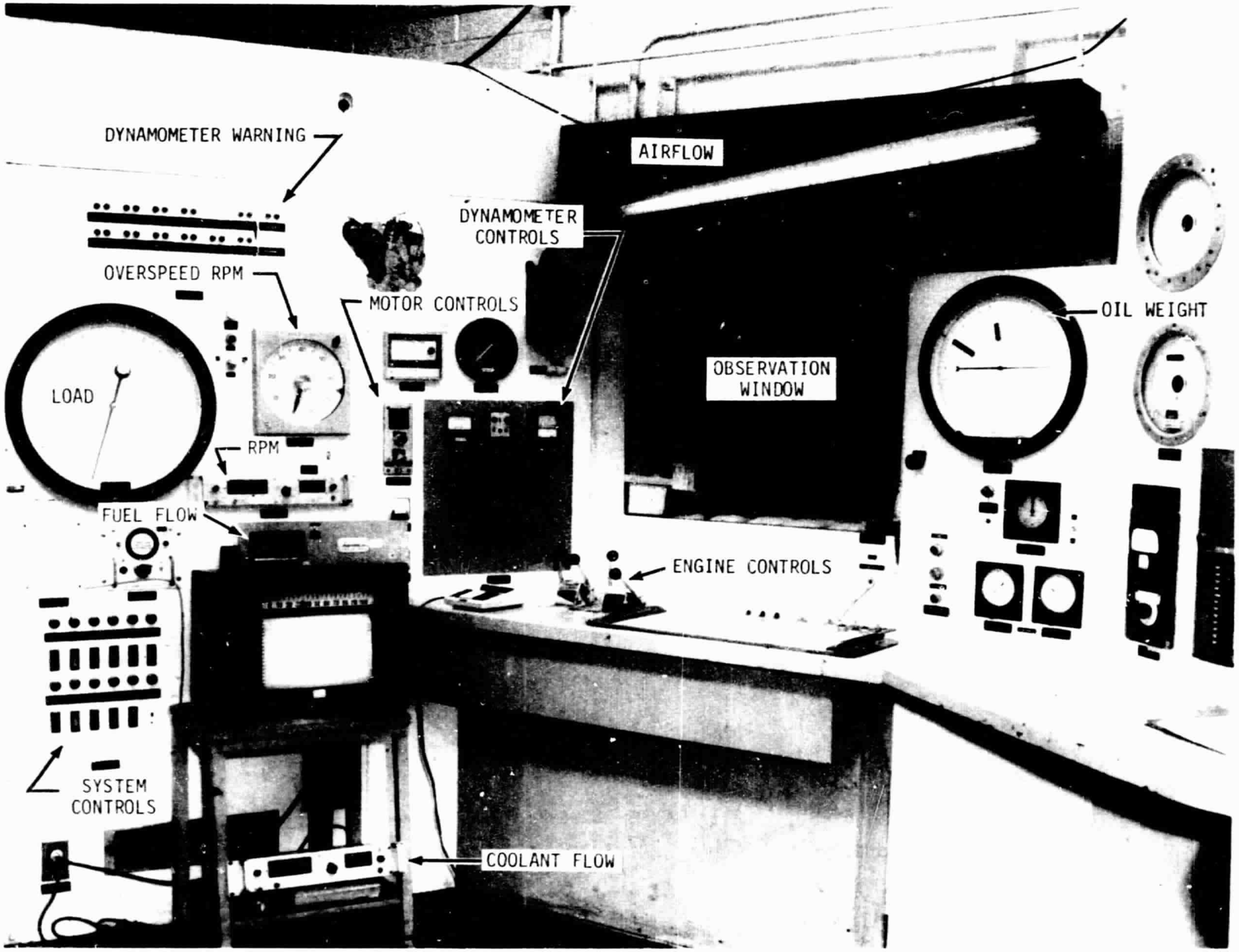

Figure 5. Tester's Control Station in the Control Room.

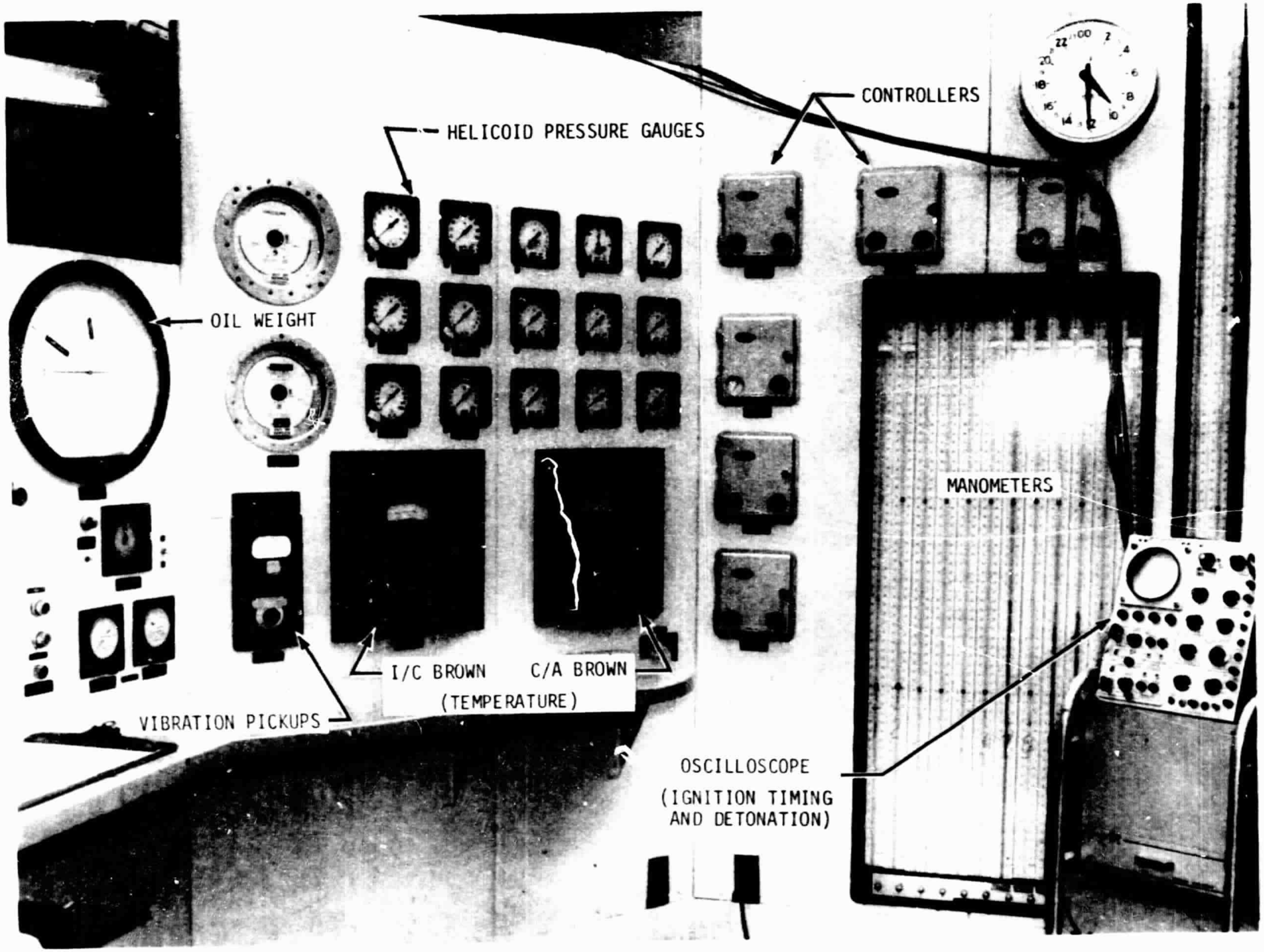

Figure 6. Right Side of the Control Room and Instruments.

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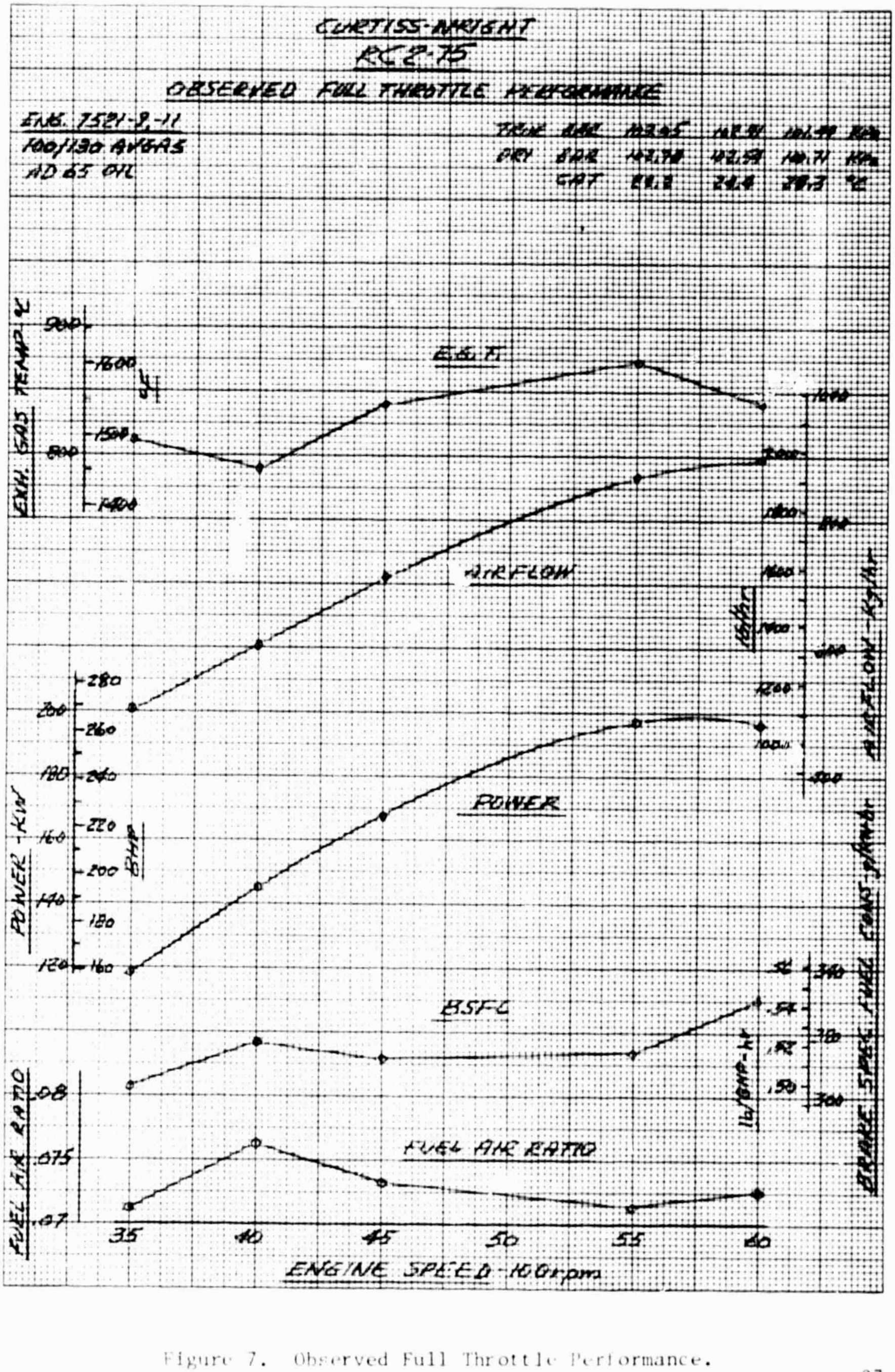

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Figure 7. Observed Full Throttle Performance.

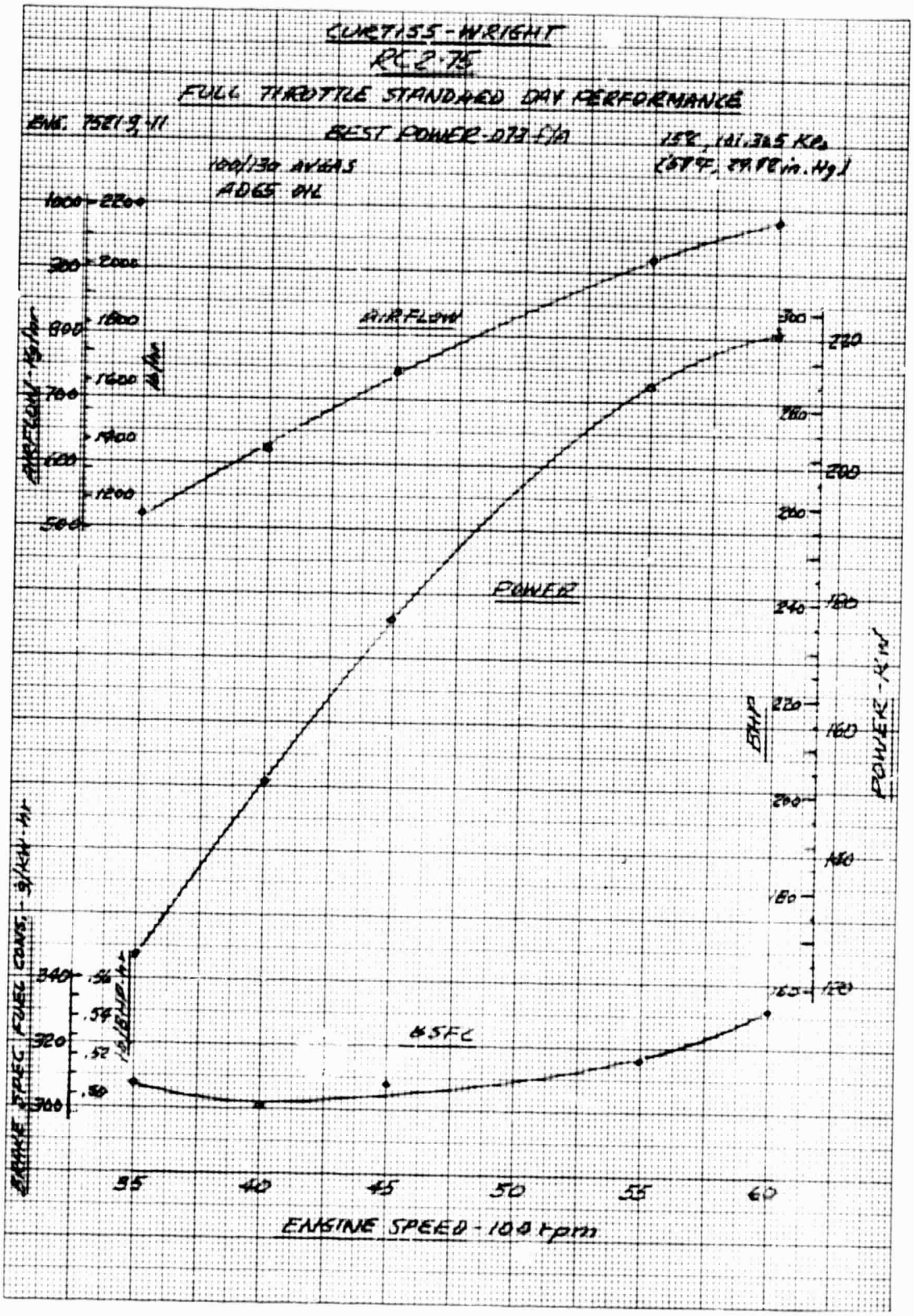

Figure 8. Full Throttle Standard Day Performance.

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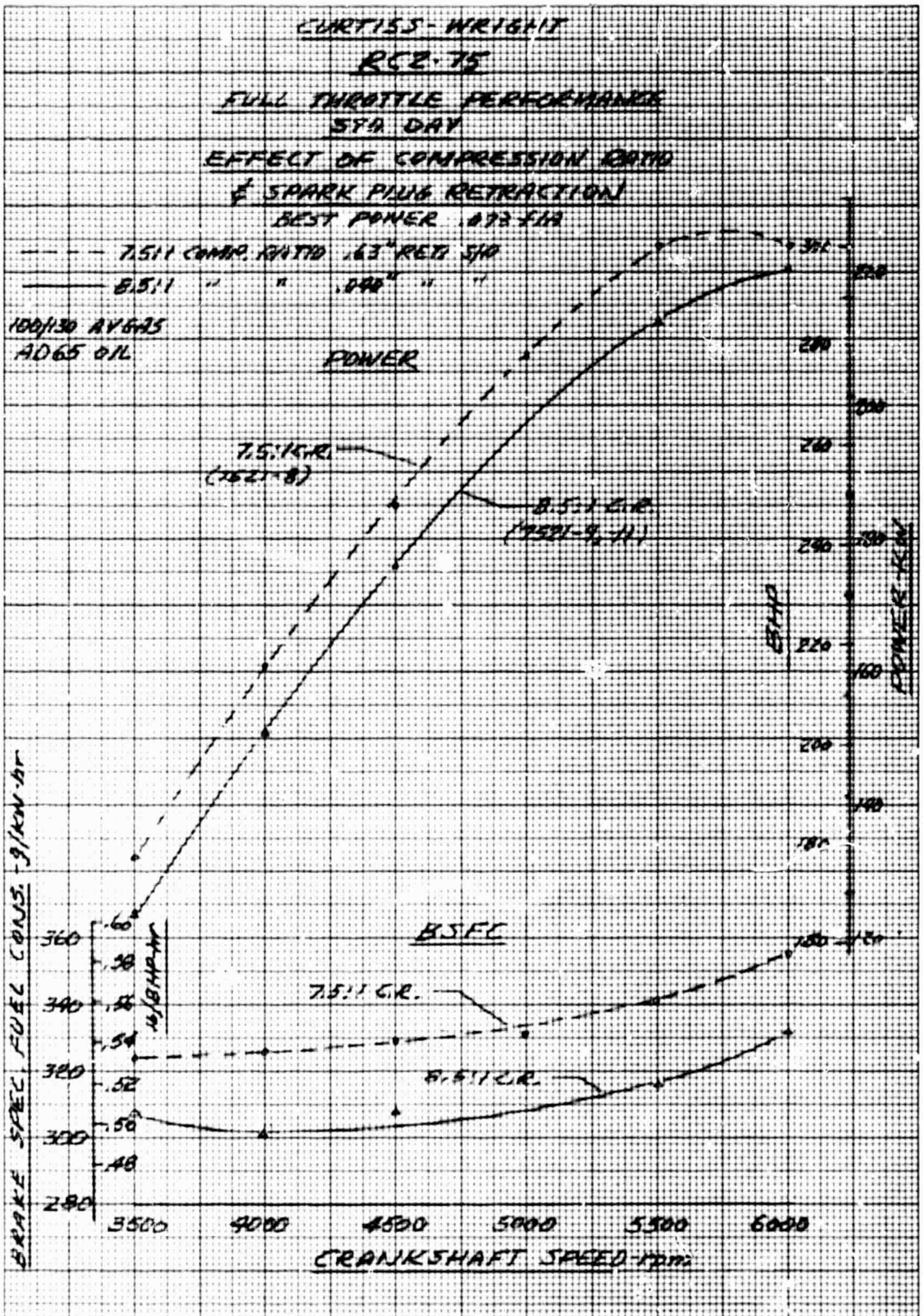

Figure 9. Full Throttle Standard Day Performance, Effect of Compression Ratic and Spark Plug Retraction.

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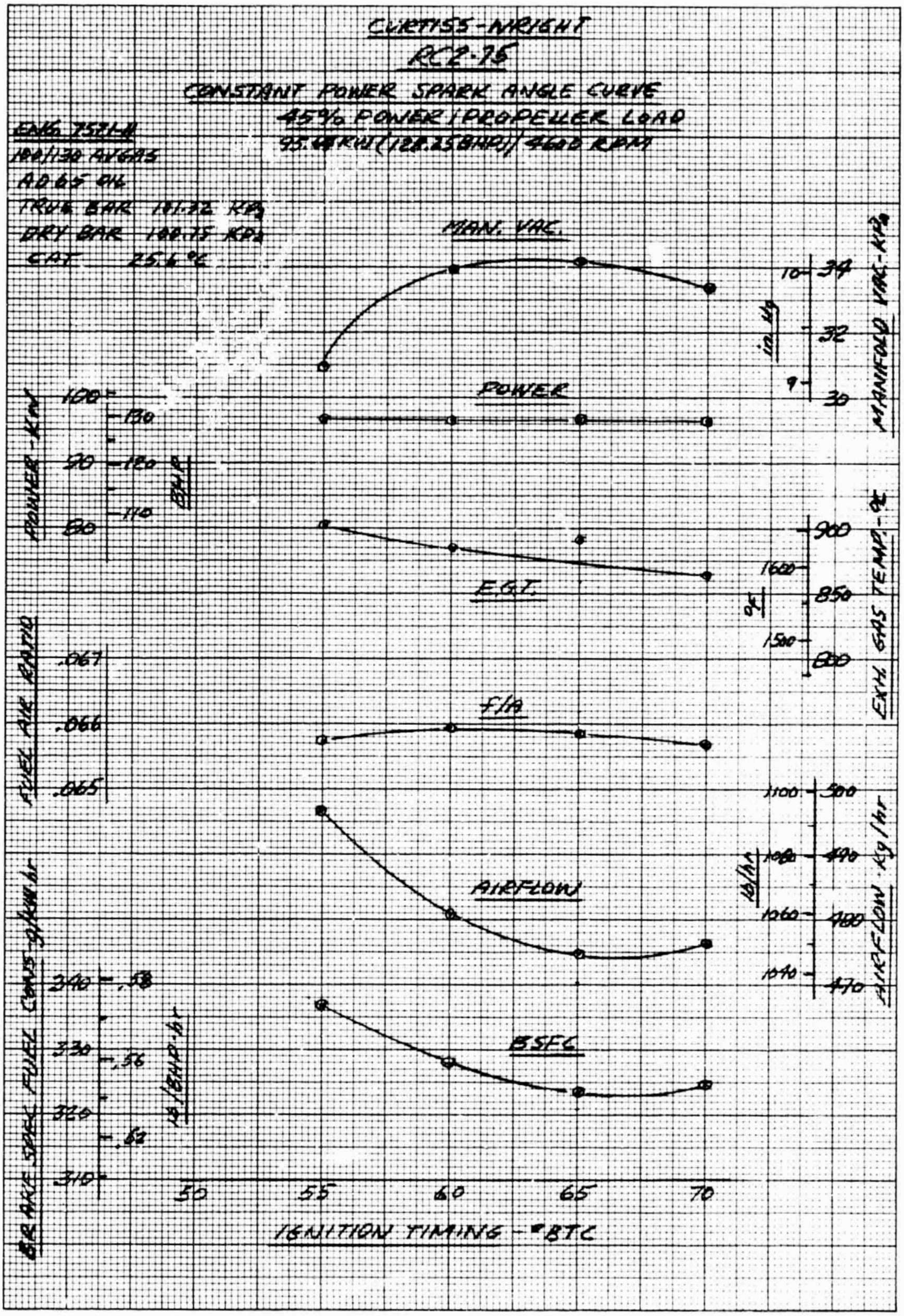

Figure 10. Constant Power Spark Angle Curve, 45% Power, Propeller Load.

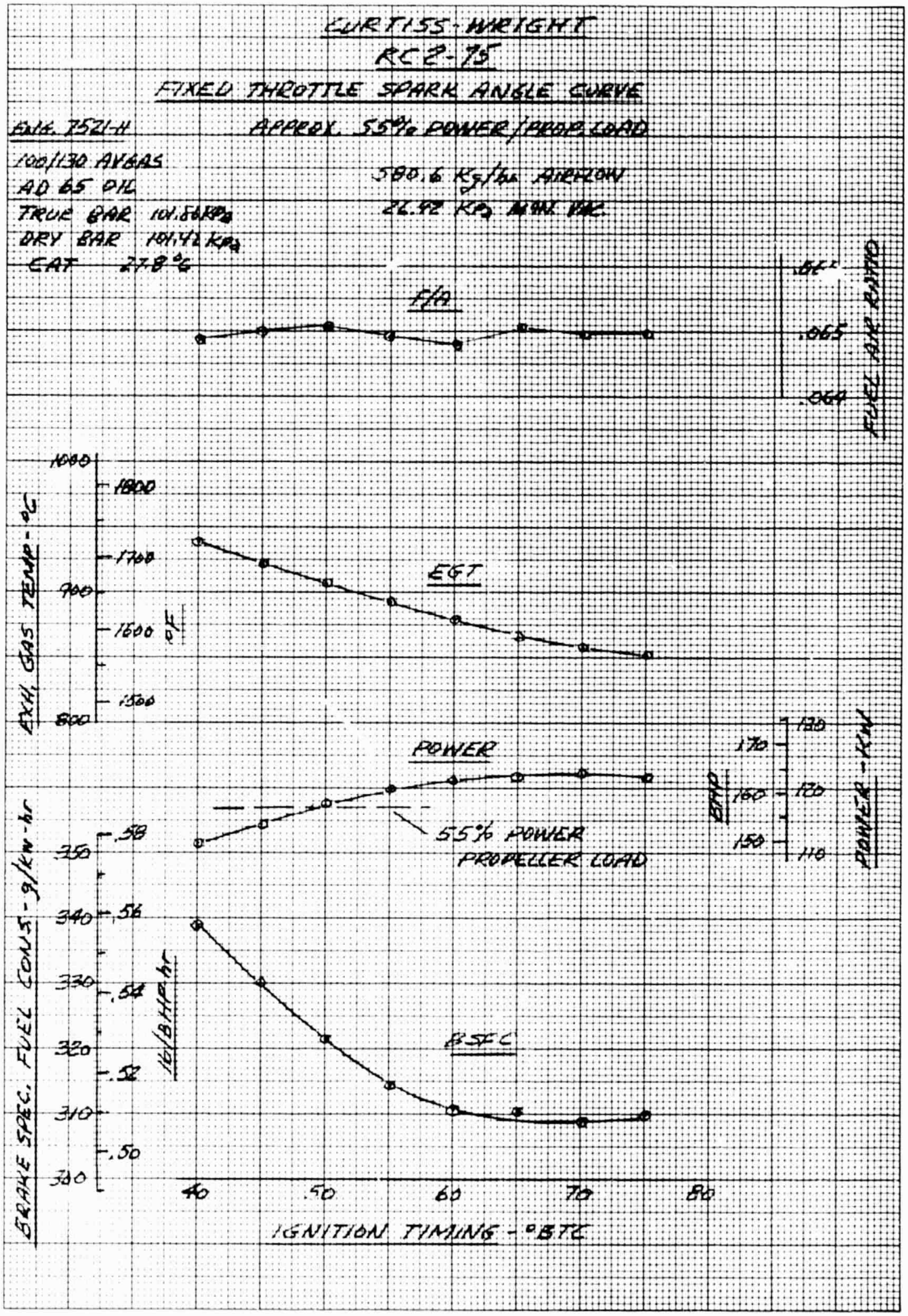

Figure 11. Fixed Throttle Spark Angle Curve, Approximately 55% Power - Propeller Load.

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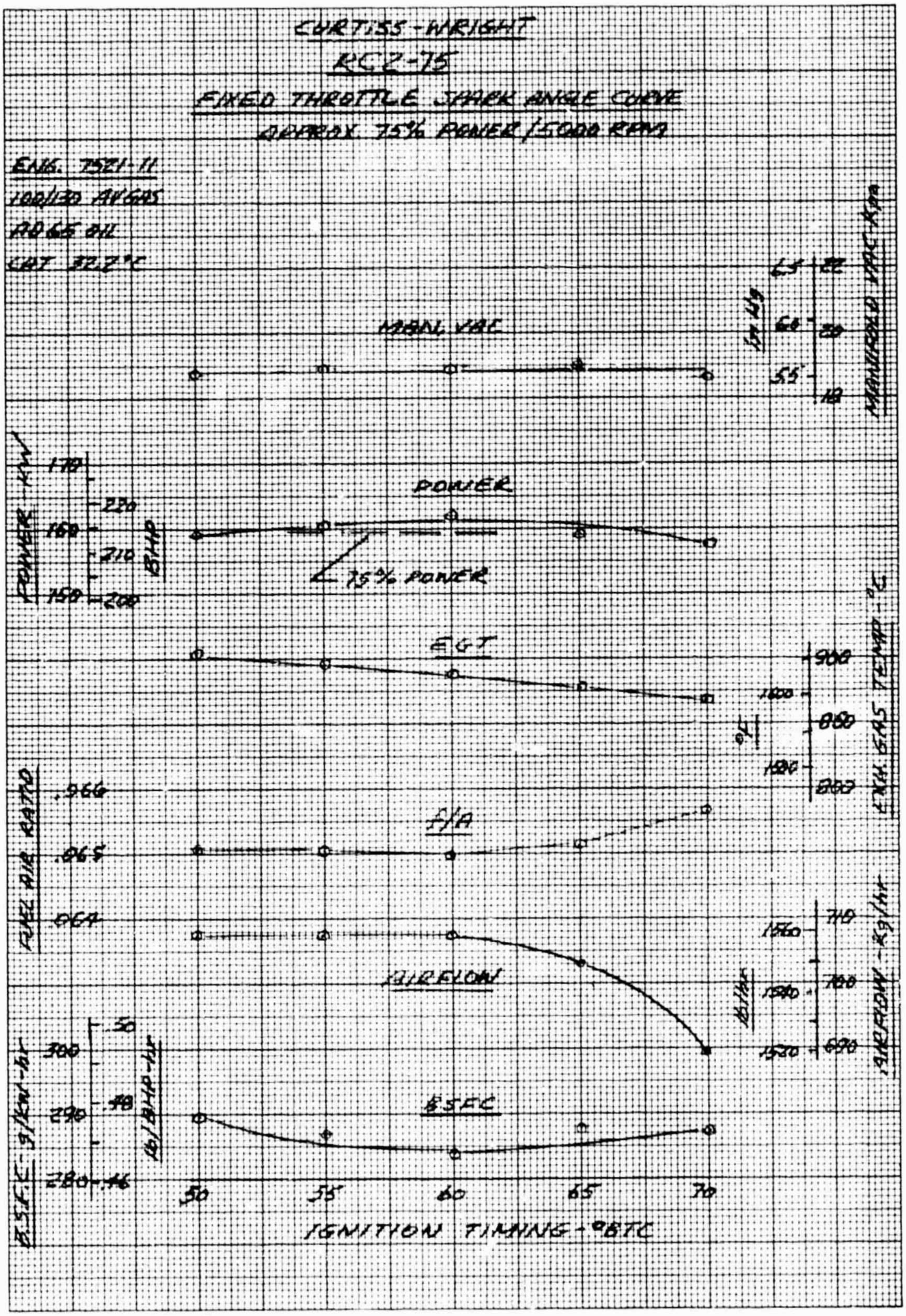

Figure 12. Fixed Throttle Spark Angle Curve, Approximately 75% Power - 5000 RPM.

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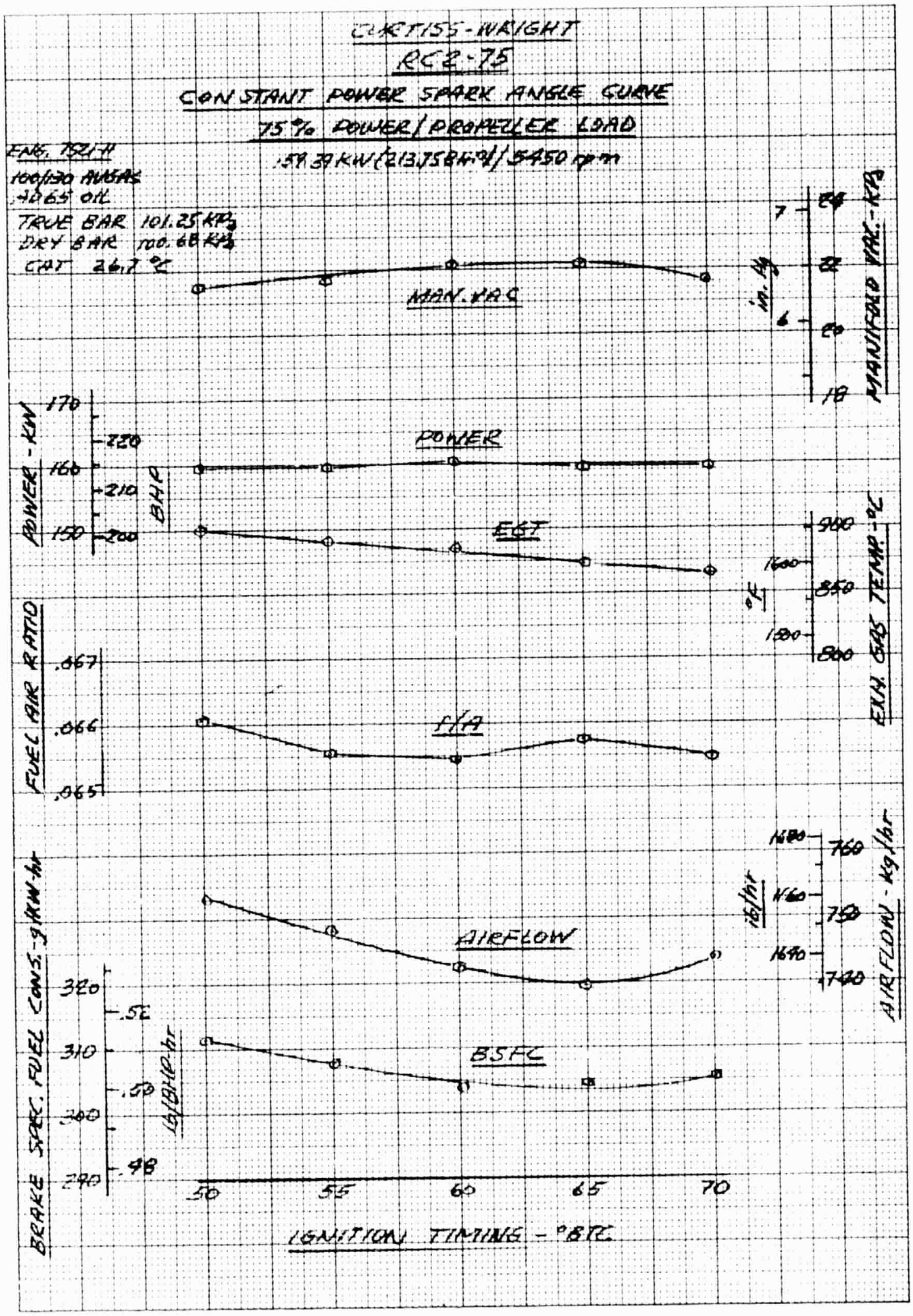

Figure 13. Constant Power Spark Angle Curve, Approximately 75% Power - Propeller Load.

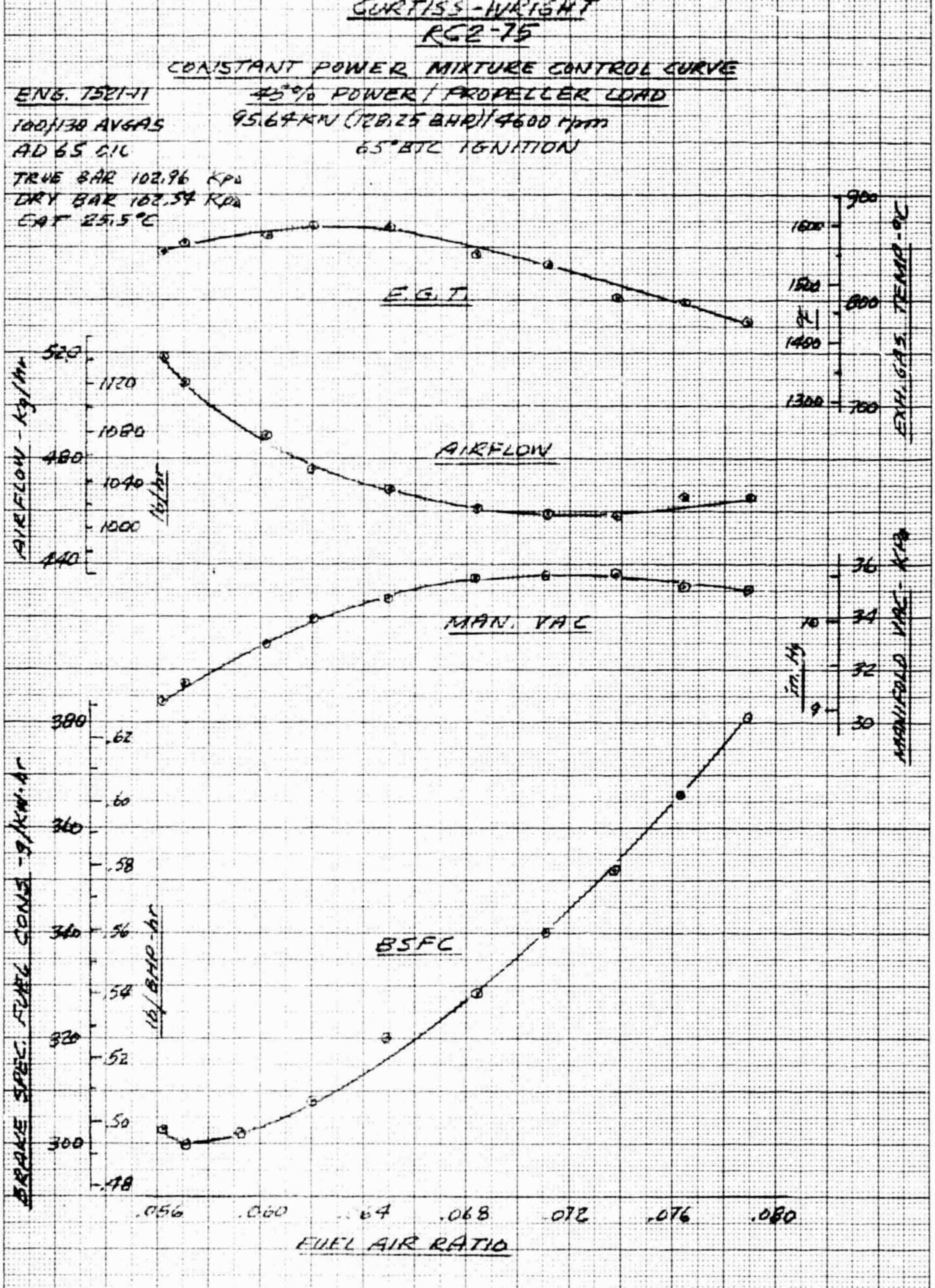

Figure 14. Constant Power Mixture Control Curve, 45% Power - Propeller Load.

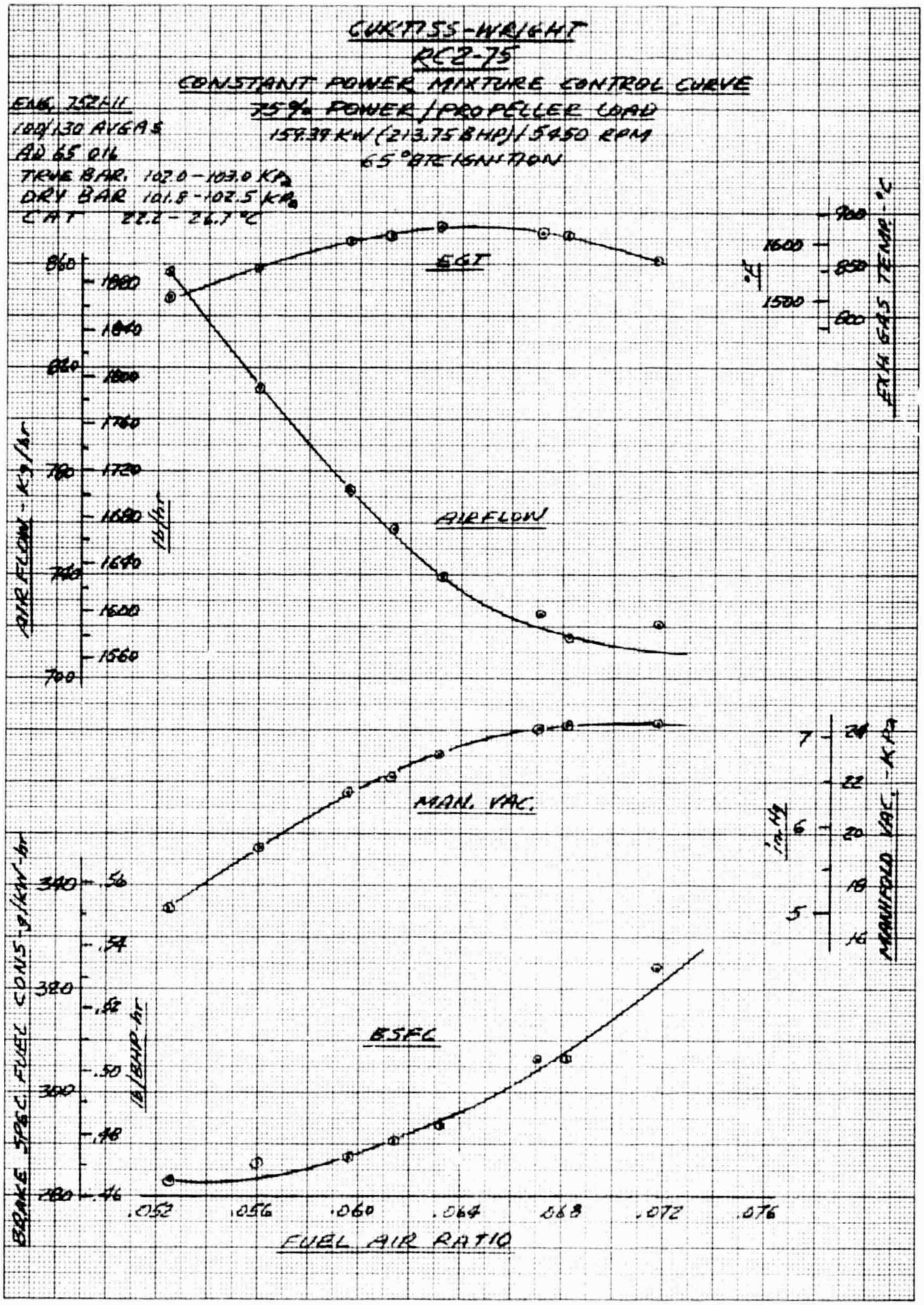

Figure 15. Constant Power Mixture Control Curve, 75% Power - Propeller Load.

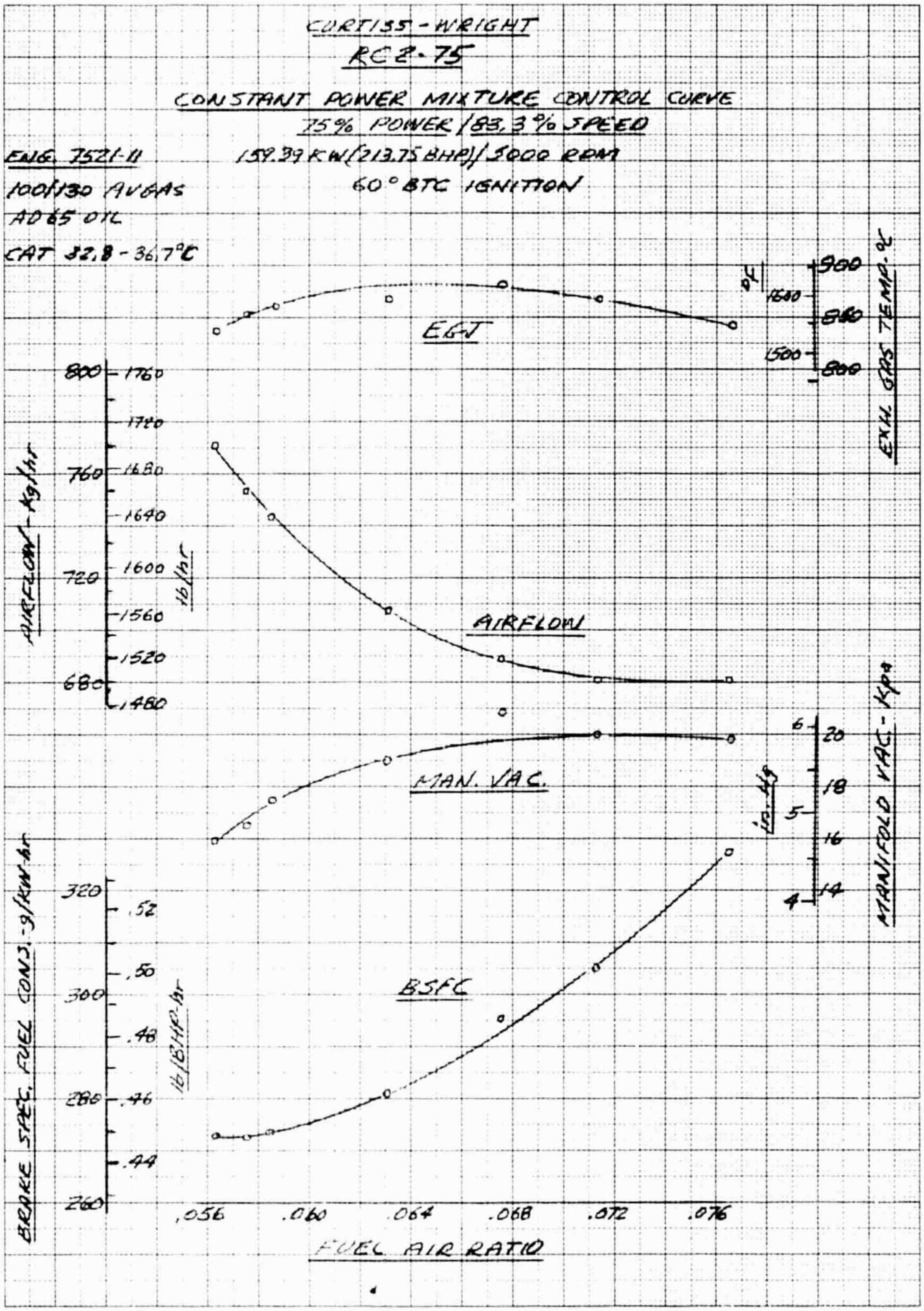

Figure 16. Constant Power Mixture Control Curve, 75% Power - Propeller Load.

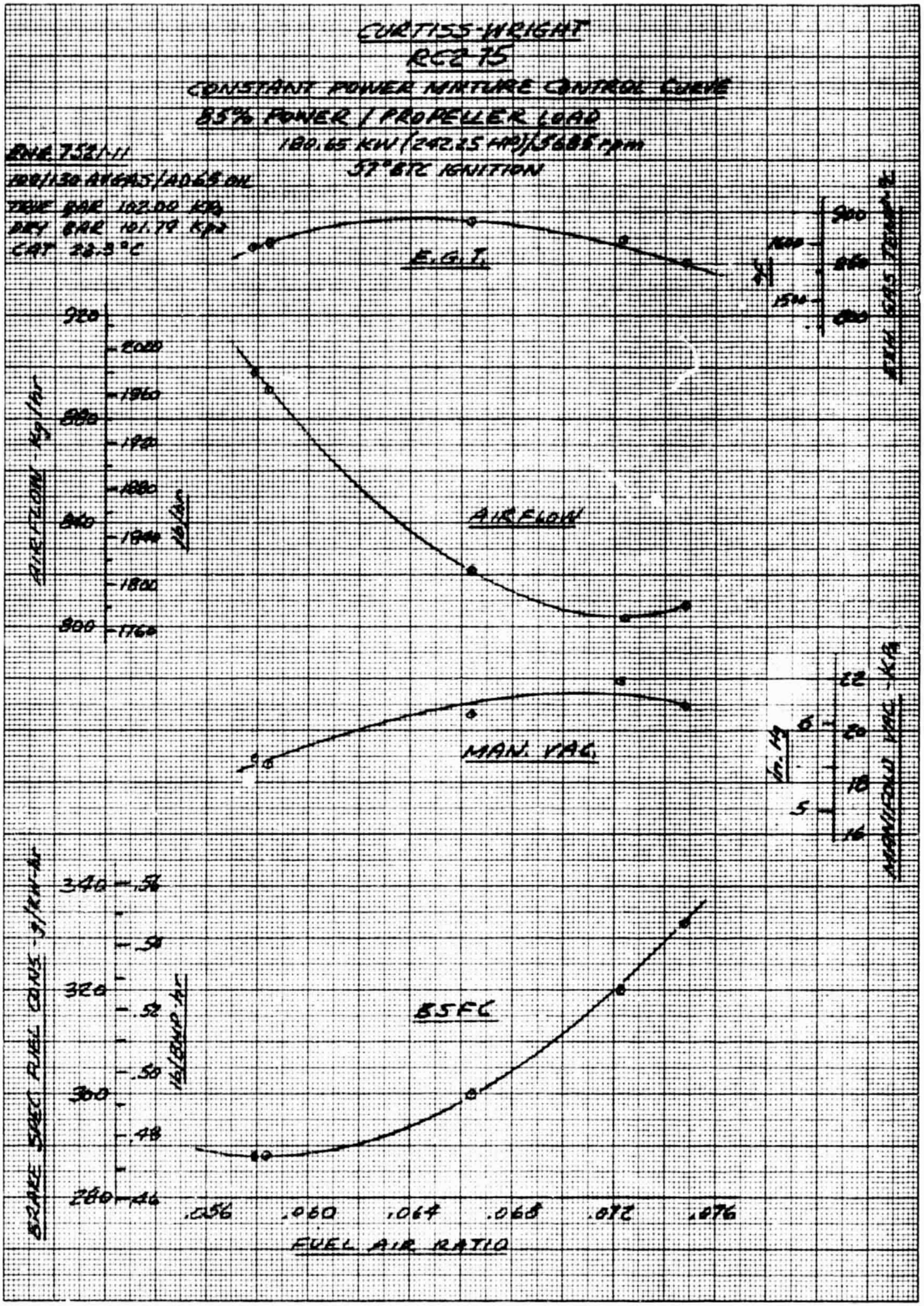

Figure 17. Constant Power Mixture Control Curve, 85% Power - Propeller Load.

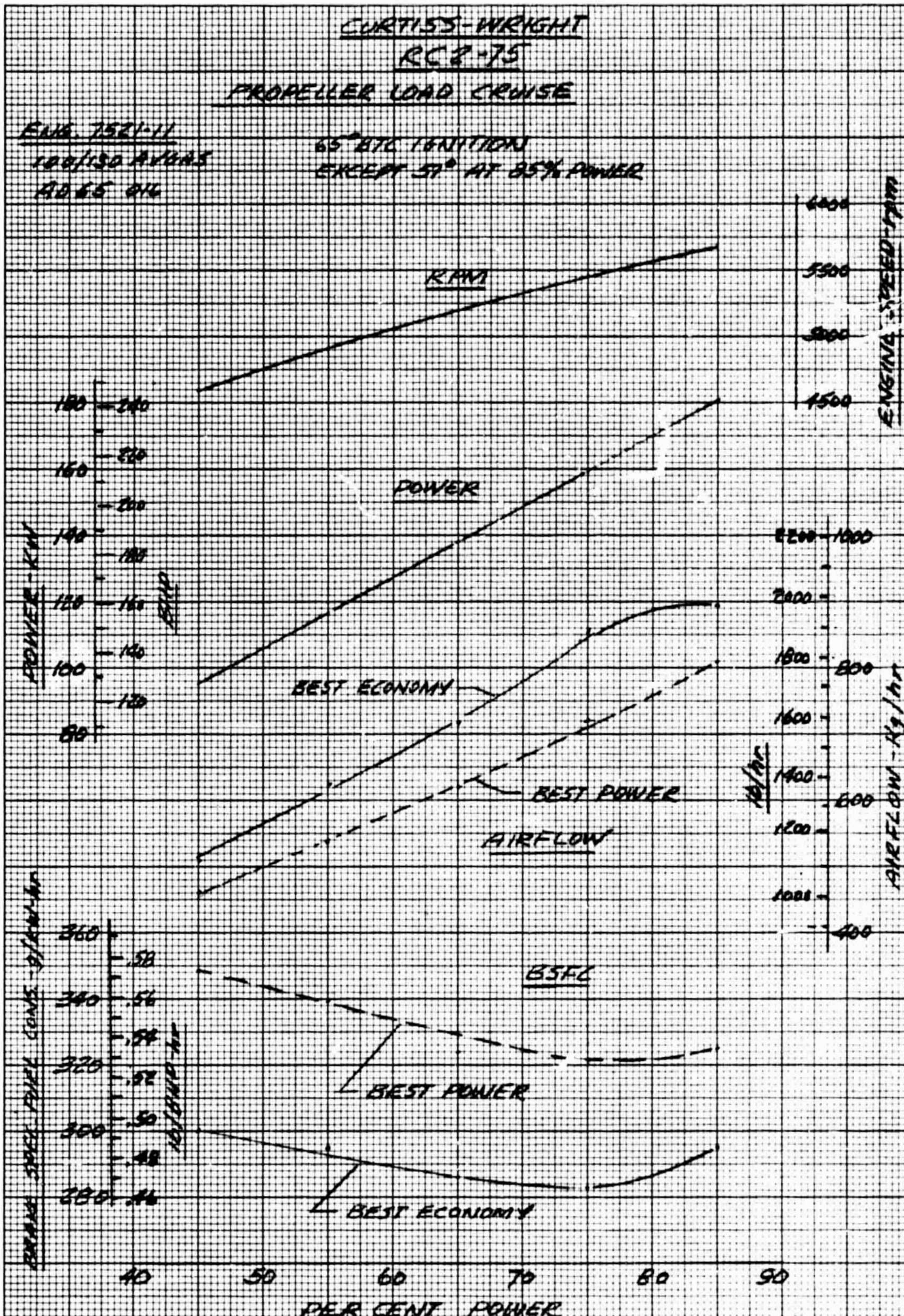

Figure 18. Propeller Load Cruise, Best Power and Best Economy.

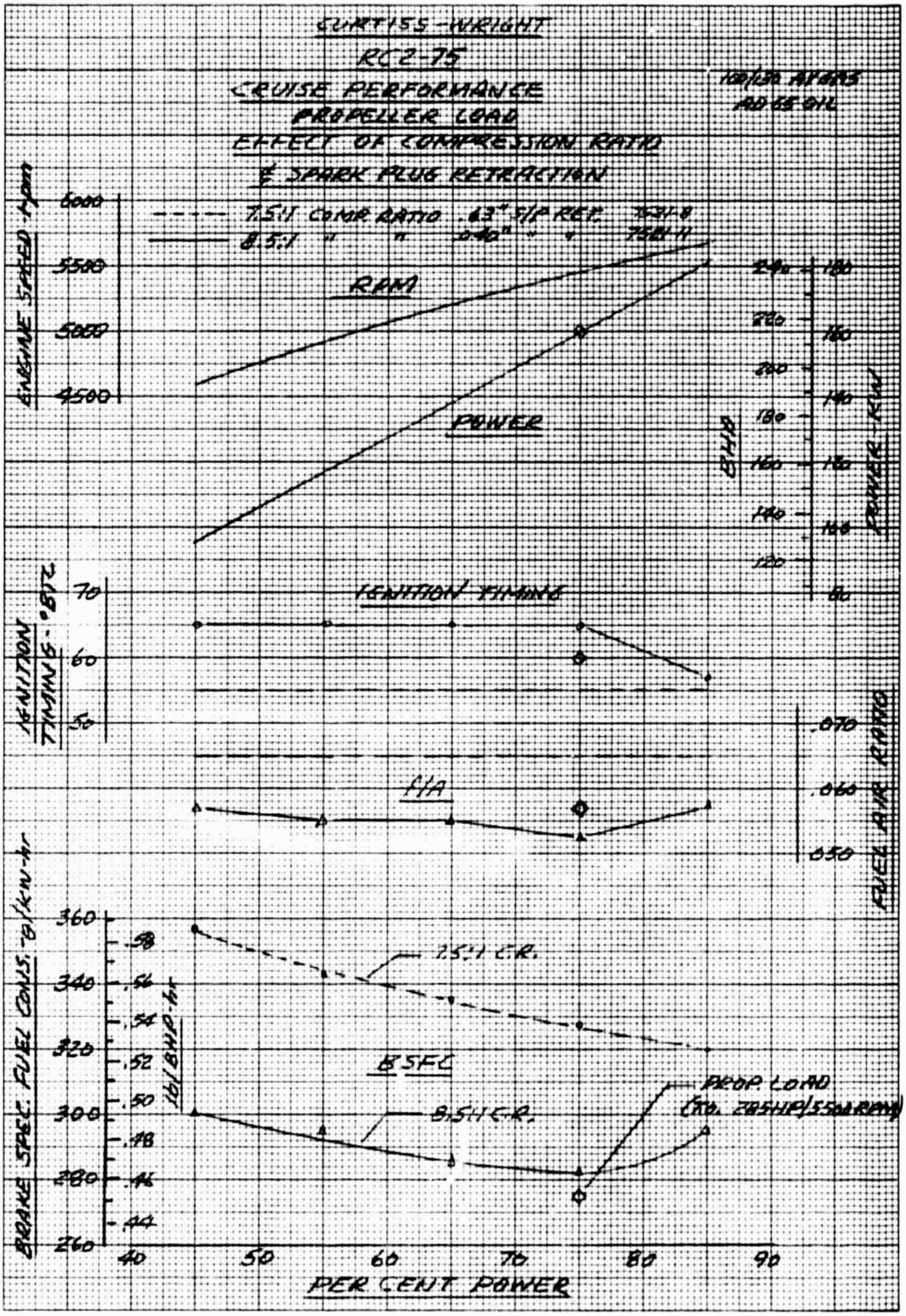

Figure 19. Cruise Performance, Propeller Load - Effect of Compression Ratio and Spark Plug Retraction.

EPA EXHAUST EMISSIONS TEST RESULTS
285 BHP Curtiss-Wright RC2-75 Engine No. 7521-9, -11
Ignition Timing 33°BTC

	Idle	Taxi	Take-Off	Climb	Approach
KW.	2.4	21	-	170	85
BHP	3.2	28	262	228	114
RPM	1330	2660	6000	5400	5200
Airflow . . . lb/hr	96.5	291	1970	1665	1000
Fuel-Flow . . . lb/hr	8.25	21.29	142.3	125.3	73.8
Air Fuel Ratio	11.69697	13.668	13.844	13.288	13.550
F/A	.08549	.07316	.07223	.07526	.07380
CO_2 . . . % Dry	7.75	11.9	12.3	12.1	12.3
CO . . . % Dry	2.5	3.4	3.1	3.7	2.85
THC . . . PPMC Wet	35700	5200	1950	2235	1935
O_2 . . . % Dry	6.9	1.3	.68	.465	.42
NO_x . . . PPM Wet	12	56	1075	855	430
H_2O . . . Correction	.98339	.87209	.86507	.86781	.87153
A/F . . . Spindt Carbon Balance	14.63369	13.66750	13.74268	13.35428	13.67249
A/F . . Stivender Oxygen Balance	13.43891	13.17668	13.55174	13.04336	13.69648
Exhaust Density . . . lb/ft^3	.071163	.073703	.073903	.073260	.07357
HC . . . lb/hr	1.91863	.80447	2.03493	1.99415	1.03118
CO . . . lb/hr	2.62725	9.12107	55.64728	56.96679	26.32062
NO_x . . . lb/hr	.00210	.02824	3.65635	2.48639	.74687
HC . . . lb/Cycle	.06395	.18771	.01017	.16618	.103118
CO . . . lb/Cycle	.08752	2.12825	.27824	4.74723	2.63206
NO_x . . . lb/Cycle	.00007	.006177	.01828	.20720	.07649

	Test	EPA Std.
HC Emissions, lb/Cycle/Rated HP	.00186	.0019
CO Emissions, lb/Cycle/Rated HP	.03464	.0420
NO_x Emissions, lb/Cycle/Rated HP	.00108	.0015

Figure 20. Table of EPA Exhaust Emissions Test Results.

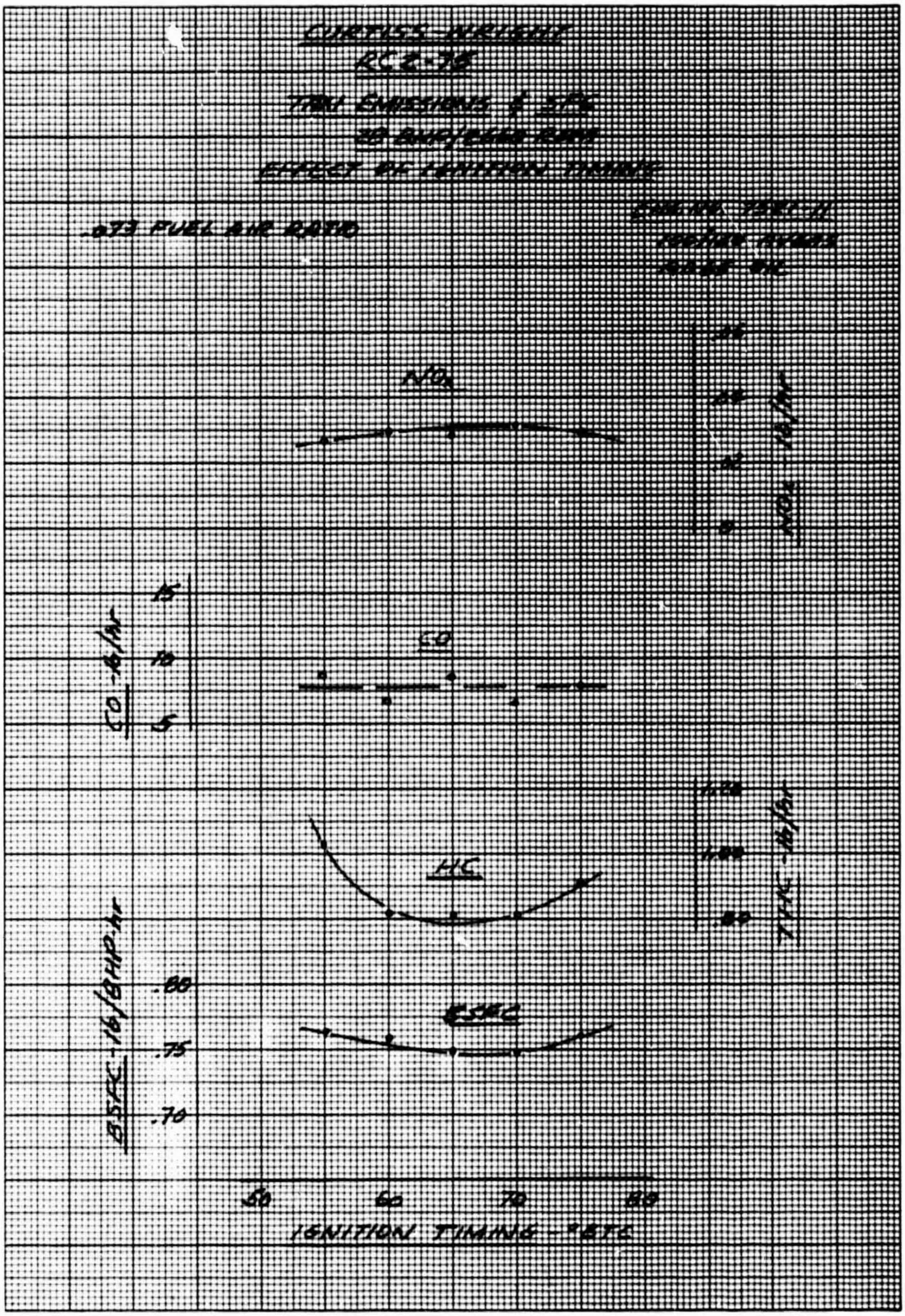

Figure 21. Taxi Emissions and SFC, Effect of Ignition Timing.

80-144

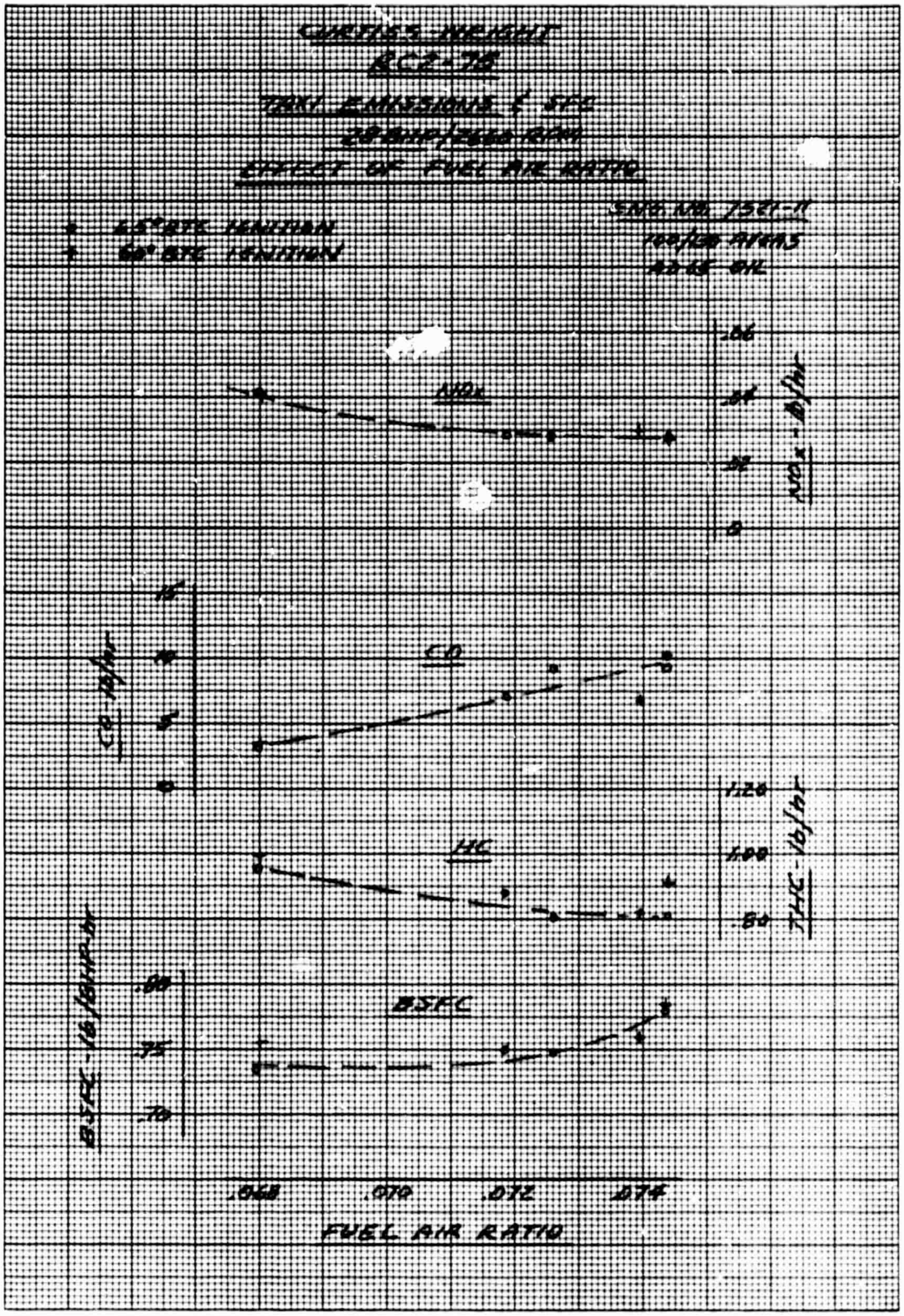

Figure 22. Taxi Emissions and SFC, Effect of Fuel-Air Ratio.

V. APPENDICES

A. Original Test Plan, dated September 15, 1978

B. Revised Test Plan, dated August, 1979

C. Modified Test Plan, dated March, 1980

D. Laboratory Analysis - Aviation Gasoline 100/130 with 1% AD65 Oil

APPENDIX A

PROGRAM FOR CHARACTERISTIC DATA OF AN EXPERIMENTAL ROTATING COMBUSTION AIRCRAFT ENGINE

Contract No. NAS 3-20808

TEST PLAN

TASK II

H. D. Lamping

Rotary Engine Facility
Curtiss-Wright Corporation
Wood-Ridge, New Jersey 07075

September 15, 1978

For

NASA-Lewis Research Center
Cleveland, Ohio 44135

APPENDIX A

TABLE OF CONTENTS

APPENDIX A

1. TEST OBJECTIVES

Characterization of a modified RC2-75 Rotating Combustion Engine as an aircraft engine. Specific objectives are to demonstrate exhaust emissions that meet the levels which had been proposed for 1980 by EPA, and to demonstrate improved fuel economy.

2. TYPE, NUMBER AND ORDER OF TESTS

The test program consists of dynamometer tests of a Curtiss-Wright owned experimental Rotating Combustion Engine which has been modified for:

a. 8.5:1 compression ratio symmetrical pocket rotors.

b. Rotor and side housings to allow use of side and peripheral intake ports independently and/or in combination.

c. Spark plugs located in rotor housings to place the spark discharge approximately 0.040 inch from trochoid surface.

The test will be conducted on Curtiss-Wright owned test facility, Dynamometer Test Cell WX20-5. Since the Dynamometer does not have adequate absorption characteristics when driven at propeller shaft speed, power will be absorbed at crankshaft speed from the flywheel end of the engine.

The test program is expected to be a continuous one in which various regimes of operation are investigated and documented. The order in which testing will be conducted is in the general format outlined herein:

a. The engine will be set up for operation on peripheral ports and will be run-in for a period of approximately 10 hours. Ignition timing will be varied at selected points to get an early indication of timing requirements. The following schedule makes up the run-in, approximately 30 minutes per point. Exhaust emissions data will not be measured during this phase.

Pt	rpm	BMEP	Pt	rpm	BMEP
1	2800	30	11	4000	40
2	2800	40	12	3000	50
3	3000	60	13	5000	80
4	3000	25	14	3000	50
5	3500	30	15	4000	70
6	4000	55	16	4000	60
7	4500	60	17	4600	73 (45%)
8	4900	83 (55%)	18	3000	90
9	3500	40	19	5450	102 (75%)
10	2800	30	20	2800	30
10a	Perform air leak check		20a	Perform air leak check	

b. Baseline Exploration - Peripheral Intake Ports

Purpose of this phase is to obtain a minimum amount of performance and exhaust emissions data for comparison with data obtained under the previous contract, and which is necessary to determine which configuration (peripheral only or combi-ports) to use in the mapping testing. The following curves will be run; exhaust emissions data will be included.

(1) Mixture control curve at 6000 rpm, full throttle
(2) Mixture control curve at 75% rated power
(3) Mixture control curve at taxi condition
(4) Idle data - several points may be required to determine proper setting of idle mixture screws.

c. Combi-Port Exploration - Peripheral and Side Ports Open

Purpose of this phase is to determine if having both ports open will have an adverse effect on take-off performance or cruise fuel economy. If not, then all subsequent testing above the taxi mode will be performed with the combi-port arrangement. The following conditions will be evaluated; exhaust emissions will be included:

(1) Mixture control curve at 6000 rpm, full throttle
(2) Mixture control curve at 75% rated power.

d. Full Throttle, Sea Level Performance (With either Peripheral or Combi-Porting, as Determined

Purpose is to provide additional full throttle data to cover operating range. Data will be obtained at 3500, 4500 and 5500 rpm.

e. Idle and Taxi - Side Intake Ports (In event side ports are required to satisfy emission standard)

Purpose is to define the effects of operating with side intake ports only (peripheral ports plugged), for comparison with data obtained in Item b. The following will be run; emissions data will be included:

(1) Mixture control curve at taxi conditions
(2) Idle data.

f. EPA Cycle

(Ref. Federal Register Volume 38, No. 136, Part II dated Tuesday, July 17, 1973)

No.	Mode	Time - Minutes
1	Idle	1
2	Taxi-Out	11
3	Take-Off	0.3
4	Climb-Out	5
5	Approach	6
6	Taxi-In	3
7	Idle	1

It will be necessary to shut down twice during the cycle to switch from one port combination to the other. If possible the engine test conditions at shutdown will be duplicated and stabilized before the emissions data is taken after restart. The data log of the emission cycle test will be sent to the project engineer as soon as it is established that the data are correct.

g. Sea Level Propeller Load Performance (With porting as determined from B and C Testing)

Purpose is to provide sufficient additional data over and above that obtained in b. or c. to characterize the prop load performance.

(1) Mixture control curve at 45% rated power.
(2) Mixture control curve at 85% rated power.
(3) Rich and lean points at 55 and 65% power.

h. Cruise Conditions (With porting as determined from B and C testing)

Purpose is to provide minimum data required to map engine performance over the normal cruise range. This data will be obtained only if time and funding permits it.

(1) 4500 rpm variable MAP (3 rich, 3 lean)
(2) 5000 rpm variable MAP (3 rich, 3 lean)
(3) 5500 rpm variable MAP (3 rich, 3 lean)

3. SCHEDULE

Figure 1 presents the schedule for engine assembly and test phase.

4. INSTRUMENTATION, MEASUREMENTS AND PRECISION

Test Data recorded will be in accordance with the listing below.

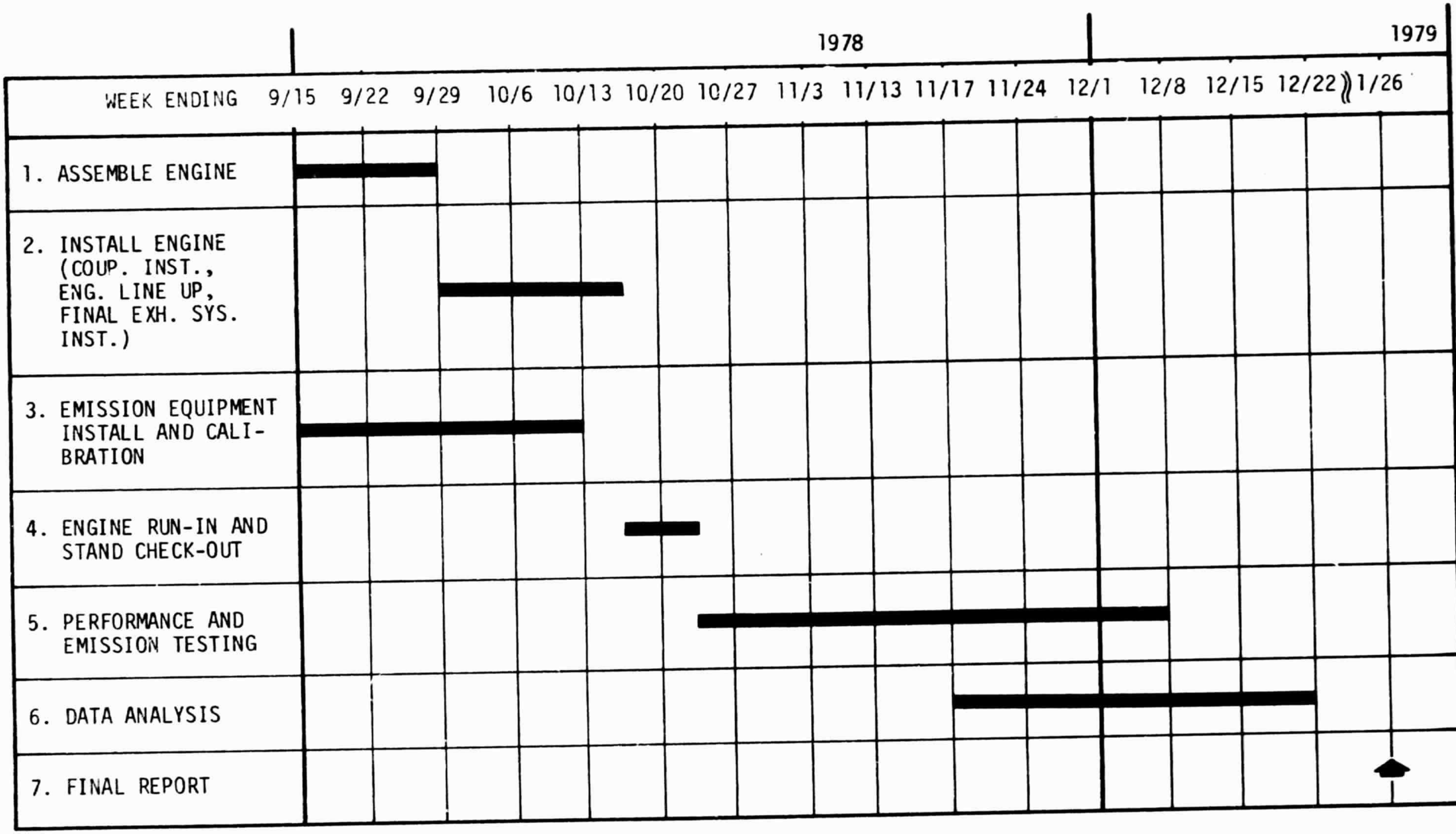

Figure 1. Rotary Combustion Aircraft Engine Characterization - RC2-75 Engine

a. Basic Engine Variables	Units	Instrumentation	Data Accuracy
Time of Day Start Stop	0-2400 hrs 0-2400 hrs 0-2400 hrs		
Total Engine Time	Hours		
Crankshaft Speed	rpm	Digital, Pre-Set Counter	± count
Ignition Timing	Degrees, BTC		± 2°
Dynamometer Load	lbs	Emery Cell	± 0.4% Load Range
BHP	-		
Airflow Fuel Flow	lbs/hr lbs/hr	 Flotron	± 0.5% ± 0.5%
S.F.C. S.A.C.	lbs/BHP-hr lbs/BHP-hr		
C.A.T.	°F	I/C Thermos	± 2°
M.P.	"Hg	Manometer	± .05 in. Hg
Oil Pressure	psig	Helicoid Gauge	± 1 psi
Oil In Temperature Oil Out	°F °F	I/C Thermo I/C Thermo	
Coolant Pressure	psig	Helicoid Gauge	
Coolant In Temperature Coolant Out	°F °F	I/C Thermo I/C Thermo	
Coolant Flow	lb/hr	(Potter Flow Meter Brown Indicator)	± 0.5%
E.G.T.	°F	C/A Thermo	± 5°
E.B.P.	"Hg		
Barometer	"Hg	(Sling Psy.) (Dry Bulb) (Wet Bulb) (Vapor Press) (Psy. Chart)	

b. Exhaust Emissions

THC	PPM Propane	Scott Model 108	$\pm$ 5%
CO, Dry	o/o	Scott Model 108	
CO_2, Dry	o/o	Scott Model 108	
O_2, Dry	o/o	Scott Model 108	
NO, Wet	PPM		
NO_x, Wet	PPM		

5. TEST SET-UP

A schematic of the engine and dynamometer drive line is shown in Figure 2.

6. METHOD OF DATA PRESENTATION

Final report will be a complete and comprehensive report on the entire program activity. Data here will generally be presented in graphical form (8-1/2" x 11" or 11" x 17" folded) with variables of interest plotted in an appropriate manner to permit notation and/or prediction of trends or relative levels. The accompanying narration will build from the graphical data as required. The variables of interest will consist of typical engine W.O.T., part throttle performance parameters, e.g. speed, power, oil and coolant temperatures (into and out of the engine), flow rates (air-fuel-coolant-oil), exhaust emissions.

7. CALCULATIONS AND CORRECTIONS

a. Basic Engine Performance Calculations

$$\text{HP} = \frac{\text{Dynamometer Load x rpm}}{\text{Dynamometer Constant}}$$

$$\text{BMEP} = \frac{\text{HP x 396000}}{\text{2 x 76.2 x rpm}}$$

$$\text{Obs. F/A} = \frac{\text{Observed Fuel Weight Flow}}{\text{Observed Air Weight Flow}}$$

$$\text{BSFC} = \frac{\text{Pounds of Fuel per Hour}}{\text{BHP}}$$

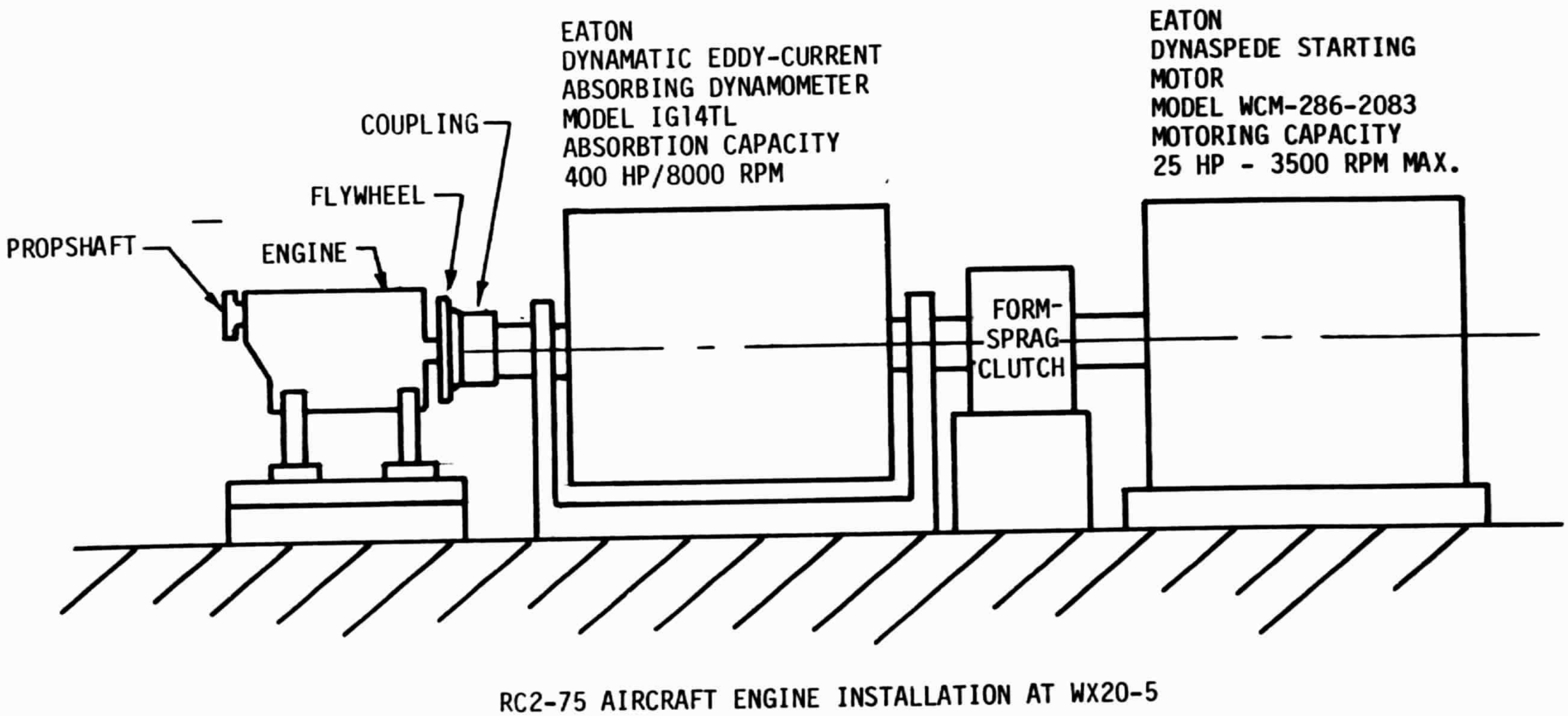

Figure 2. Schematic of the RC2-75 Engine and the Dynamometer Drive Line System

b. Full Throttle Performance Corrections

Brake Horsepower

$$(1)\quad BHP_{std} = (BHP_{obs} + FHP)\left(\frac{29.92}{B_D - \Delta_P}\right)\sqrt{\frac{CAT + 459.4}{518.4}} - FHP$$

where FHP = friction horsepower

B_D = true barometer - vapor pressure, in. Hg

Δ_p = airflow system pressure drop, in. Hg

CAT = carburetor air temperature, °F

Airflow

$$(2)\quad Airflow_{std} = (airflow_{obs})\left(\frac{29.92}{B_T - \Delta p}\right)\sqrt{\frac{CAT + 459.4}{518.4}}$$

where B_T = true barometer, in. Hg

Brake Specific Fuel Consumption

$$(3)\quad BSFC_{std} = (f/a_{act})\left(\frac{AF_{std}}{BHP_{std}}\right)$$

$$\text{where } f/a_{actual} = (f/A_{obs})\sqrt{\frac{1 - .377\frac{Pv}{Pw}}{1 - \frac{Pv}{Pw}}}$$

$$\text{and } \frac{Pv}{Pw} = \frac{BD}{BT} - 1$$

where the correction factor accounts for the water vapor in the measured wet airflow

c. Exhaust Emission Calculation Formulae

Wet Correction Factor for Water of Combustion and Ambient Humidity

A procedure used in the general aviation industry will be utilized as follows:

$$(1)\quad \frac{H_2O}{1-H_2O} = \left[2+7.67478\left(\frac{W}{a}\right)\right]$$

$$\left[\frac{\frac{(CO_2)+(CO)+(THC)}{100}(12.01+1.008y)}{138.2689\ (f/a)}\right]-\left[\frac{2[(CO_2+O_2)]+(CO)+(NO)}{100}\right]$$

where ( ) = % concentration of exhaust constituents

with CO, CO_2 and O_2 dry and NO and HC wet

as measured

f/a = measured fuel air ratio

y = hydrogen carbon ratio

and w/a, the inlet air specific humidity

$$w/a = .622\ \frac{(\text{true barometer} - \text{dry barometer})}{\text{dry barometer}}$$

(2) From the above, the correction factor, Cf_w, derives as

$$Cf_w = \frac{1}{1+\frac{H_2O}{1-H_2O}}$$

Calculation of Air-Fuel Ratio

The Spindt carbon balance procedure, reference 3, will be utilized as follows:

$$(3)\quad A/F = Fb\left[11.492\ Fc\left(\frac{1+\frac{R}{2}+Q}{1+R}\right)+\frac{120\ (1-Fc)}{3.5+R}\right]$$

where $R = \frac{(CO)}{(CO_2)}$ $Q = \frac{(O)}{(CO_2)}$ $F_b = \frac{(CO)+(CO_2)}{(CO)+(CO_2)+(THC)}$

and $Fc = \frac{12.01}{12.01+1.008y}$

An oxygen balance calculation procedure for air-fuel ratio by Stivender, reference 4, will be utilized

$$(4) \quad A/F = 4.76 \left(\frac{\frac{(H2O) + (NOx) + (CO)}{2} + (CO2) + (O2)}{(CO) + (CO2) + (THC)} \right) \frac{28.96}{M_f}$$

where $(H_2O) = 100 (1 - Cf_w)$

and $M_f = 12.01 + 1.008y$

a carbon balance procedure of calculating air-fuel ratio, also by Stivender, reference 4, will be utilized

$$(5) \quad A/F = \frac{28.96}{M_f} \left(\frac{\frac{3(H_2O) - (CO)}{2} + (THC) + 100}{(CO) + (CO_2) + (THC)} - \frac{y}{2} \right)$$

Calculation of Exhaust Gas Density

From Figure 57 (Curtiss-Wright Engineering Handbook, 1965) showing the gas constant, R, versus f/A for varying hydrogen carbon ratio the following was derived to determine exhaust gas density for the exhaust volume mass emissions calculations.

$$(6) \quad f/a_t = (.9558 - F_h) \ .086$$

where $F_h = \frac{1.008y}{12.01}$

if the observed f/A is equal to or less than f/a_t the gas constant is calculated

$$(7) \quad R_1 = \left[(F_h - .1) \ 453.33 + 120 \right] f/a + 43.2$$

if the observed f/A is greater than f/a_t the gas constant is calculated

$$(8) \quad R_r = \left\{ \left[\left(\frac{R_1}{53.345} - 1 \right) \frac{f/a}{f/a_t} \right] + 1 \right\} 53.345$$

the exhaust gas density results from

$$(9)\quad d_{exh} = \frac{(14.7)(144)}{(528)\ R} = \frac{4.009}{R},\ lb/ft^3$$

Mass Emission Rates

Exhaust Volume Method

$$(10)\quad X,\ lb/hr = \left(\frac{FF + AF}{d_{exh}}\right)(X)\quad(d_x)$$

where FF = fuel flow, lb/hr

AF = airflow, lb/hr

(X) = concentration of pollutant wet

d_{exh} = exhaust gas density at 68°F, 760 mm Hg

d_x = density of pollutant

Carbon Balance Method

$$(11)\quad X,\ lb/hr = \frac{(X)\ (V)\ (d_x)}{100}$$

where V = exhaust flow, lb/hr

$$= \left(\frac{100}{(THC) + (CO) + (CO2)}\right)\left(\frac{FF}{M_f}\right)(N)$$

where ( ) = % concentration of pollutant wet

M_f = 12.01 + 1.008y

N = 385 ft^3/lb mol at 68°F, 760 mm Hg

APPENDIX B

PROGRAM FOR CHARACTERISTIC DATA OF AN EXPERIMENTAL ROTARY COMBUSTION AIRCRAFT ENGINE

Contract No. NAS 3-20808

TEST PLAN (MODIFIED)

TASK II

I. Manning

Rotary Engine Facility
Curtiss-Wright Corporation
Wood-Ridge, New Jersey 07075

August, 1979

For

NASA-Lewis Research Center
Cleveland, Ohio 44135

APPENDIX B

TYPE, NUMBER, AND ORDER OF TESTS

1. The engine will be set up for operation on peripheral ports, and will be run-in for a period of approximately 5 hours. Ignition timing will be varied at selected points to get an early indication of timing requirements. The following schedule makes up the run-in, approximately 30 minutes per point. Exhaust emissions data will not be measured during this phase.

Pt	rpm	BMEP	Pt	rpm	BMEP
1	2800	30	6	2800	30
2	3000	35	7	4000	40
3	3500	40	8	4600	73 (45%)
4	4000	55	9	5450	102 (75%)
5	4900	83 (55%)	10	2800	30

Perform air leak check

2. Baseline performance testing with peripheral ports. Exhaust emissions data will not be measured during this phase.

   a. Full Throttle, Sea Level Performance

   To provide full throttle data over the operating range, best power points at speeds of 3500, 4500, and 5500 rpm will be run.

   b. Sea Level Propeller Load Performance

   This is to provide sufficient data to characterize the prop load performance.

   - Mixture control curve at 45% rated power (128.3 BHP/4600 rpm)
   - Mixture control curve at 75% rated power (213.8 BHP/5450 rpm)
   - Mixture control curve at 85% rated power (242.3 BHP/5685 rpm)
   - Rich and lean points at 55% and 65% rated power (156.8 BHP/4915 rpm and 185.3 BHP/5200 rpm)

3. Performance testing with peripheral intake ports with exhaust emissions data included.

   a. The following curves will be run:

   - Mixture control curve at 6000 rpm, full throttle

- Mixture control curve at 75% rated power (213.8 BHP/5450 rpm)

- Mixture control curve at taxi conditions (28 BHP/2660 rpm)

- Idle Data - several points may be required to determine proper setting of the idle mixture screws.

b. Should the emissions of the taxi and idle tests of item 3.a. above not appear to reduce overall cycle emissions sufficiently to meet EPA standards, then the following would be accomplished.

<u>Idle and Taxi - Side Intake Ports</u> (In event side ports are required to satisfy emission standard)

Purpose is to define the effects of operating with side intake ports only (peripheral ports plugged), for comparison with data obtained in 3.a. The following will be run; emissions data will be included:

- Mixture control curve at taxi conditions

- Idle data

APPENDIX C

PROGRAM FOR CHARACTERISTIC DATA OF AN EXPERIMENTAL ROTARY COMBUSTION AIRCRAFT ENGINE

Contract No. NAS 3-20808

TEST PLAN (MODIFIED)

TASK II

I. Manning

Rotary Engine Facility
Curtiss-Wright Corporation
Wood-Ridge, New Jersey 07075

March, 1980

For

NASA-Lewis Research Center
Cleveland, Ohio 44135

APPENDIX C

TYPE, NUMBER, AND ORDER OF TESTS

Based upon verbal discussions between Curtiss-Wright Corporation and NASA-LEWIS personnel on 27 February 1980, the following test effort was proposed to further identify fuel consumption characteristics of the RC2-75 model engine:

- Operate the engine at 5000 rpm and 111 BMEP, while varying the fuel flow and spark advance sufficiently to establish best specific fuel consumption. Approximately 12-20 test points will be run to establish the data point.

- Results of the effort will be included in the contract final report to be released in April 1980.

LABORATORIES AT KENILWORTH, N. J. PHILADELPHIA, HAMMOND, IND., NEW ORLEANS, PASADENA (HOUSTON), CORPUS CHRISTI, WILMINGTON, CALIF., SEATTLE, PORTLAND, ORE., TAMPICO, MEX., CHICAGO, BOSTON, AND WEST HAVEN, CONN.

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LABORATORY ANALYSIS REPORT

APRIL 18, 1979
LAB. NO. 6495

SAMPLE DESIGNATED BY CLIENT AS AVIATION GAS

FROM SUBMITTED: MARCH 23, 1979

P.O. # RC-204453

FOR CURTISS-WRIGHT CORPORATION
ONE PASSIAC STREET
WOOD-RIDGE, NEW JERSEY

(1L) 775

TESTS	RESULTS
GRAVITY, API @60°F	66.4
HYDROGEN CARBON RATIO	5.816
COLOR	GREEN
CORROSION 2 HRS @ 212°F	PASSES # 1
SULFUR	0.01%
VAPOR PRESSURE REID @100°F	1.4 LBS.
ANILINE POINT	144°F
LEAD	1.61 G/GAL
NET HEAT OF COMBUSTION	18863 BTU /LBS.
POTENTIAL GUM	2.0 MGS.
FREEZING POINT	BELOW MINUS 72°F
WATER REACTION	0.5 ML # 1
I.B.P.	96°F
10% EVAPORATED AT	146°F
40% EVAPORATED AT	204°F
50% EVAPORATED AT	212°F
90% EVAPORATED AT	234°F
END POINT	300°F
RECOVERY	98%

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BY Rodger L. Cuthbert

PAGE 1

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APPENDIX D

LICENSED INSPECTION
APPROVED GAUGERS BY U.S. CUSTOMS
INSPECTION OF PETROLEUM AND OTHER PRODUCTS
GENERAL HEADQUARTERS
400 SWENSON DRIVE
KENILWORTH, N. J. 07033

CABLE ADDRESS "SAYBOLTOIL"

GULF COAST HEADQUARTERS
P. O. BOX 4364
PASADENA, TEXAS 77502
(713) 447-8171

WEST COAST HEADQUARTERS
P. O. BOX 1146
WILMINGTON, CALIF. 90744
(213) 835-8383

EAST COAST HEADQUARTERS
400 SWENSON DRIVE
KENILWORTH, N. J. 07033
(201) 245-3100

SERVING THE PETROLEUM INDUSTRY FOR OVER 70 YEARS
DEPENDABLE INSPECTION SERVICE AT ALL PORTS ON THE ATLANTIC, GULF AND PACIFIC COASTS

LABORATORY ANALYSIS REPORT

APRIL 18, 1979
LAB. NO. 6495

SAMPLE DESIGNATED BY CLIENT AS AVIATION GAS

FROM SUBMITTED: MARCH 23, 1979

P.O. # RC-204453

FOR CURTISS-WRIGHT CORPORATION
ONE PASSIAC STREET
WOOD-RIDGE, NEW JERSEY

(1L) 775

TESTS	RESULTS
RESIDUE	1.0%
LOSS	1.0%
RESIDUAL ACIDITY	NONE
SUMS OF 10% AND 50% EVAPORATED AT	355°F
EMISSION SPECTROGRAPH	CAN'T RUN

E. W. SAYBOLT & CO., INC.

BY Rodger L. Cuthbert

MEMBERS OF A. S. T. M. – A. P. I. – S. A. E.

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